Institute of Geography and Spatial Management
Jagiellonian University
Baltic University Programme
Tatra National Park

Sustainable water resources management in high mountains in the Baltic Sea Region

Edited by Joanna Pociask-Karteczka

Kraków 2019

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Zygmunt Górka, Tomasz Bryndal, Wiesław Ziaja

Front cover
The Kasprowy Wierch Cable Car in the Tatra National Park
(Photo. J. Pociask-Karteczka)

Back cover
Logo of the the 2nd International Tatra Hydrological Workshop
on Sustainable water resources management
in high mountains in the Baltic Sea Region
(Designed by K. Mostowik)

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Contens

What are you saying to me, mountain stream?
Where, in which place, do we meet?
Do you meet me who is also passing – just like you…
But is it like you?

"The Roman Triptych", 2003, John Paul II

Foreword

Mountains play important role in human's live.They cover 24 percent of the Earth and are home to 12 percent of the world's population. Mountains are rich repositories of water and biodiversity, they provide of ecosystem goods on which downstream communities rely. Over half of humanity's freshwater originates in the mountains. Unfortunately mountains represent the most fragile environment on Earth, and they are particularly vulnerable to changes. Mountains are facing enormous pressure from various anthropogenic impacts and drivers of global scale, including climate change. Those factors influence mountains' environment, including water. Realising the importance of mountains as environment of crucial significance for water resources both in local and regional scales, the Institute of Geography and Spatial Management – Jagiellonian University in Cracow, the Baltic University Programme and the Tatra National Park developed the 2nd Tatra Hydrological Workshop on *Sustainable water resources management in high mountains in the Baltic Sea Region* (10-13 June 2019, Zakopane, Poland) dedicated to students as well as young scientists. The aim of the workshop was to get a relevant knowledge about monitoring and sampling techniques for analyzing hydrological processes, and organizing a monitoring network to control the influence of human activities (tourism, ski, water and energy supply municipal system) on the quantity and quality of water resources in high mountain catchments. During field works participants of the workshop had opportunity to take part in hydrological measurements with modern instruments and observe a hydrological monitoring system operating in the Tatra National Park. They get a diploma and 3 ECTS.

This book relates to lectures given during the 2nd Tatra Hydrological Workshop and has been written to provide participants of the workshop with a wide-ranging problems of water resources management in high mountains environment.

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Joanna Pociask-Karteczka

Chapter 1

Development of high mountain regions – why sustainable?

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Abstract: Mountainous regions cover a third of the Eurasian landmass. Their role in sustainable development is reviewed with Agenda 2030 and its 17 sustainable development goals adopted by the United Nations in 2015 as reference. Mountainous regions play a key role in the provision of water to their surrounding landscapes, a role which is weakened by the ongoing global warming, leading to melting glaciers and changing precipitation patterns. Mountainous regions are also hosting a wonderful diversity of species and play an important role for the protection of our biological heritage. This is now threated by infrastructure development for hydropower, mining and partly wind power leading to e.g. road building and deforestation. Mountains serve as a refuge for a large part of society by offering unique experiences of nature and wildlife and outdoor recreation, as statistics for visits to mountains proves, and requires sometimes restriction of mountain tourism. The wish for a secure access to these services has led to early implemented nature protection of mountain regions and serves as a counter force to a continued exploitation.

Keywords: environment, resources, human needs, exploitation, development

INTRODUCTION

Since the decision on a new agenda for global development for the period up to 2030, Agenda 2030, by the United Nations in the autumn of 2015 (UN 2015), followed by the Paris Agreement on limiting global warming to 2.0°C (or if possible 1.5°C) by the 21st Conference of the parties of the UN FCCC (UN FCCC 2015) not many can disregard the necessity to include sustainable development in their plans and work. This should apply foremost to politicians, but in reality it looks like the political community is the slowest to accept this agenda. The academic community, the civil society and even the business community with industry and the service sector have so far done much more than the politicians to support and develop Agenda 2030.

Sustainable development (SD) is a transdisciplinary and all-embracing undertaking so no area of human life and activity is outside, as outlined in some detail in the Sustainable Development Goals (SDGs, UN SDGs 2019) which is the document connected to the Agenda 2030. Here I will focus on the development of high mountain regions and analyse in which way SD is a concern for such areas. Formally mountains are addressed by Goal 15 *Life on Land* and its Target 15.4: "By 2030, ensure the conservation of mountain ecosystems, including their biodiversity, in order to enhance their capacity to provide benefits that are essential for sustainable development", but all the SDGs are relevant.

Sustainable development concerns how the natural world and the human society can live in harmony. It requires that both sides have a future within the limits set by the natural conditions. Thus nature need to be respected by society and natural resources used within the limits set by their replenishment. Presently we live in a situation of over-exploitation of our nature. No part of our society and no part of our planet is unaffected by the present un-sustainable development, a dilemma which has become even more apparent with the recent aggravated climate change impacts. The need for a change is obvious and the change required is drastic: a transition to a sustainable future will require major changes, but not to a more difficult life, rather the opposite. We will all profit from a transition.

The conditions which nature requires for its long term sustainability and resilience has been examined in a number of studies. These have led up to the concept of planetary boundaries, that is, boundaries within which we have to live to safeguard a future for our nature and society as we know it. So far nine planetary boundaries have been examined in some detail and quantified (Rockström et al. 2009).

The social and economic conditions which our society need to address for its sustainability has equally been examined. Here it is less obvious what could constitute a sustainable society since there is no "natural condition" which should be conserved or may serve as reference. Nevertheless the conditions were examined in detail in the 17 sustainable development goals and their 256 targets. How to stay within the natural borders and still enjoy welfare and good life such as good health, no poverty, access to food etc. has been analysed i.a. by Raworth (2017).

Roughly 24% of the Earth's landmass can be considered mountainous (Fig. 1.1). The figure varies slightly depending on the chosen definition. The largest mountainous coverage is found in Eurasia (33%), followed by North America (24%), South America (19%), and Africa (14%; World Atlas 2018). In the Baltic Sea region we find the Scandinavian Mountains at the border between Sweden and Norway, the Carpathian Mountains extending all the way from Czech Republic, Slovakia and the Polish-Ukrainian border to Romania and Serbia and the Sudeten Mountains which cover parts of Czech Republic (Bohemia and northern Moravia) bordering on Poland and further to the border to Germany (Rydén 2012a).

Thus we find high mountain regions all over the world, and they play an important part in our lives and contribute to the wellbeing of many people. In particular they have been important for access to nature and allow us to be part of the natural world. Data for the Swedish mountains (*the fjell*) concludes that about 1.4 million people out of 10 million Swedish population visits the mountains every year, and over a five year period almost half of the population has visited the mountains at least once (Statistics Sweden 2018).

Some aspects which are among the most relevant for safeguarding the sustainability of high mountain regions will be analysed here. They include water access, climate change and biodiversity (Fig. 1.2).

Water resources

Mountains sustain our societies by being the most important resource for fresh water. Many rivers originate in mountain regions and as they flow to lower lands they provide the entire landscape and its inhabitants with the necessary water. Mountains are water-rich because of the precipitation. The Baltic Sea region as a whole has an average annual precipitation of 400 mm

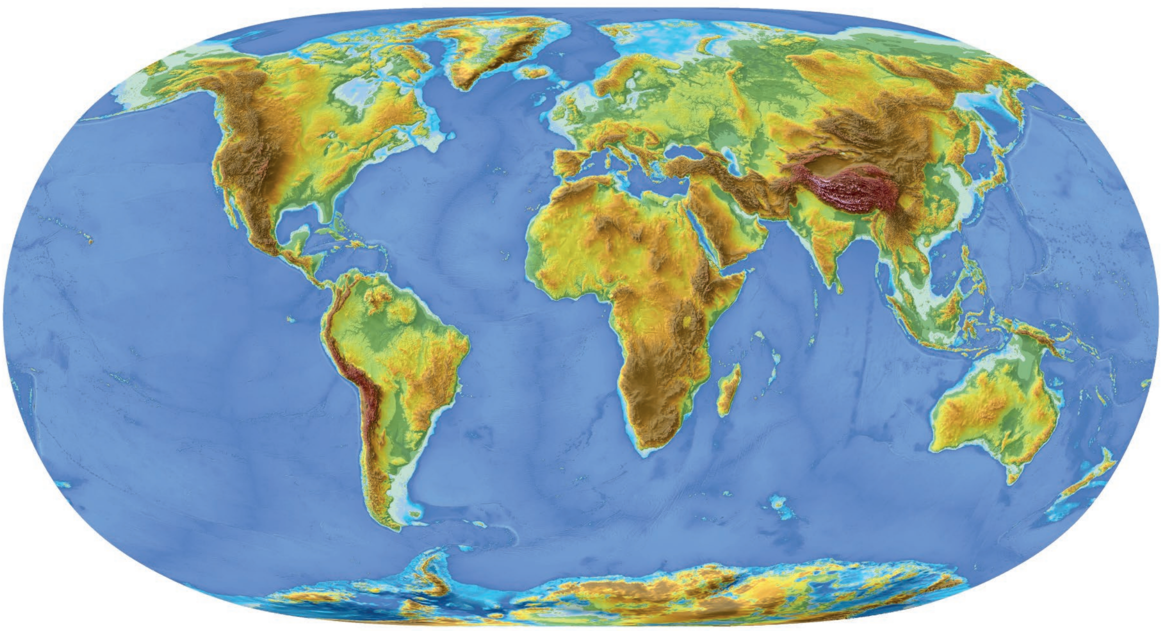

Fig. 1.1. A digital elevation model of the Earth (mountainous regions in dark colour, based on https://www.ngdc.noaa.gov/).

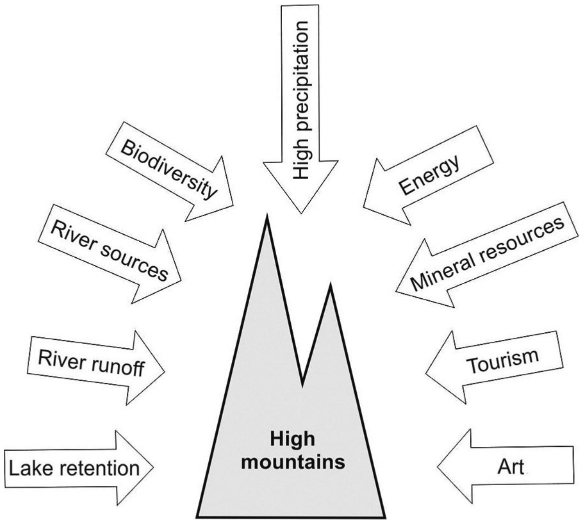

Fig. 1.2. Major contribution of mountains to human life and environment.

(Håkanson et al. 2003b). This figure is much higher in mountainous areas. On the Norwegian west coast at high altitudes it is the largest in the region of about 3000 mm. Water either goes directly into rivers and streams or it stays frozen in glaciers and thus constitutes a reservoir of water released when the glaciers melt during the warmer period. This life-giving function which mountains serve on our planet is threatened by global warming. Glaciers all over the world are decreasing in size as the average temperature raises (a summary is found in Wikipedia 2018). This is particularly strong in the northern arctic areas where mean temperature increase is much higher than the global average. Stockholm Resilience Centre (2019) for their 2019 special event celebrating the 200th Stockholm Seminars writes: "Water is essential for life on Earth and the prosperity of human civilization. As it flows through rivers and streams, rests in lakes and oceans, circulate through the roots and leaves of plants and falls as rain or snow, water serves as the bloodstream of the biosphere."

Global warming has impacted glaciers all over the world. Mid-latitude mountain ranges such as the Himalayas, the European Alps, Rocky Mountains, and the southern Andes, are showing some of the largest proportionate glacial losses (Retreat… 2018). In France all six of the major glaciers are in retreat. On Mont Blanc, the highest peak in the Alps, the Argentière Glacier, once 9 km in length, has receded 1150 m since 1870. The formerly highest Swedish peak, Kebnekajse South Peak, has lost an average of 1 meter height per year over the last 20 years and is no longer the highest mountain peak in the country (Stockholm University 2018).

The continued retreat of glaciers will have a number of different quantitative effects. In areas that are heavily dependent on water runoff from glaciers that melt during the warmer summer months, a continuation of the current retreat will eventually deplete the glacial ice and substantially reduce or eliminate runoff. A reduction in runoff will affect the ability to irrigate crops and will reduce summer stream flows necessary to keep dams and reservoirs replenished. As an example Central Asia through Amu Darya and Syr Darya is dependent on the seasonal glacier melt water for irrigation and drinking supplies. In Norway, the Alps, and the Pacific Northwest of North America, glacier runoff is important for hydropower (Retreat… 2018).

Water scarcity is one serious aspect of unsustainability today, and access to fresh water is one out of nine planetary boundaries. The consequences of different types of human activity over the 20th century until present time on freshwater, include effects of changes in land use (e.g. intensified or extended agriculture, deforestation) and water use (e.g. related to hydropower development). These have led to an increased loss of freshwater to the atmosphere due to human-driven increase of evapotranspiration, which includes evaporation from surface and soil water and transpiration by plants. On average over the Earth's land surface, the combined effect of the different human activities is a net consumption of freshwater, which is greater than the freshwater planetary boundary (Rockstrom et al. 2009). New results (Jaramillo, Destouni 2014) are more alarming than previous assessments of the freshwater planetary boundary.

Biodiversity

Mountainous areas belong to the most biodiverse regions of the planet. The large variation of ecosystems and climate along the mountain slopes, from warm forested valleys to the colder above tree-line regions is connected to a high biological diversity. The development and formation of new niches in mountains is also a ground for evolution and formation of new species. Mountainous areas typically have very many red listed species. Species endemism, in particular, often increases with altitude within mountain regions, partly due to the isolation of populations and the speciation processes over geological time scales. For example, the Caucasus Ecoregion has the highest level of endemism in the temperate world, with over 6 500 vascular plant species, at least 25 % of which are unique to the region (Antonelli et al. 2018).

The Tatra National Park protects one of the most important centres of biodiversity in Poland, a conspicuous refuge for natural richness. More than 90% of vascular plant mountain flora known from Poland occurs here, half of these taxa having their only Polish populations in this area. Similar situation concerns many other groups of organisms. The Tatra Mountains can be considered as a northernmost centre of endemism in Europe (Mirek, Ronikier 2004).

Many mountain regions are still in good conditions. The mountains were typically not heavily populated and were often left alone, thus not significantly polluted, and rare species of the flora and fauna have survived. They often also constitute a refuge for large carnivores, such as wolves, bears, lynx, and wolverine, as well as many bird species, for example the large owls. They are also home to some unique animals such as the reindeer in the north and the Tatra chamois. In many cases the rivers, brooks and lakes are undestroyed and host several valuable fish species.

On the global scale and as a whole biodiversity, however, is the most threatened natural resource and the most severely exceeded of the planetary boundaries. Mountain ecosystems are especially fragile and vulnerable to changes due to their particular and extreme climatic and biogeographic conditions. It is thus crucially important to take steps for the protection of mountainous ecosystems and diversity. The main pressures on mountain biodiversity are caused by changes in land use practices, infrastructure development, unsustainable tourism, overexploitation of natural resources, fragmentation of habitats, and climate change.

Many mountain areas have been carefully monitored by researchers and authorities, which is a good background for protective action. A moderate and careful land use is a key for the conservation of biodiversity. Also here there is often a good monitoring and statistics regarding agriculture, forestry, fishery and their certified conduct should be available. The reports to the Convention on Biological Diversity (CBD), to which almost all countries in the world belong is a very good source for regular information on biodiversity. The Biodiversity Information System for Europe (BISE) is a single entry point for data and information on biodiversity supporting the implementation of the EU strategy and the Aichi targets in Europe (BISE 2019).

Since mountains were earlier considered of less economic interest it was easy to agree on protection status. The first national park was created in the Swedish *fjell* already in 1909. It has been followed by many protected areas in all of the countries in the Baltic Sea region. The mountains areas of the Baltic Sea region is thus biologically and environmentally mostly of very high quality and by many considered a unique and common heritage to be protected and kept for us and future generations. The Tatra National Park belongs to the important elements of European and worldwide network of protected natural areas; it is well expressed, among others, by its status as an UNESCO Biosphere Reserve, Natura 2000 site and one of the European Important Plant Areas (Rydén 2012a).

In Sweden the 233 habitat types listed in Annex I to the Habitats Directive, 42 are exclusively or almost exclusively linked to mountains and 91 also occur in mountain areas. Some 21% of the conservation status assessments of mountain habitats are favourable and 60% are unfavourable. In most countries the proportion of habitat types with a favourable status is higher in the mountains than outside them. From the species listed in the Habitats Directive 181 are exclusively or almost exclusively linked to mountains, 130 are mainly found in mountains and 38 occur in mountains but mainly outside them (Axelsson Linkowski, Lennartsson 2011).

Infrastructure development in mountainous areas – hydropower, wind power and mining

Too often our traditional view of the mountains as virgin areas of wilderness is no longer valid. We see increasingly the development of roads, hydropower, mining, tourism etc. The areas are threatened in many ways: habitat destruction by land use changes and fragmentation especially by the deforestation, the building of roads and reservoirs; by pollution, especially of POPs, mercury, PCB and DDT which effect life forms either as immediately toxic or by reducing reproduction; by unsustainable too extensive hunting and fishing, and sometimes by invasive foreign species.

Deforestation is a main concern. In the Swedish mountains severe conflicts have developed as forest companies pursue timbering in forests with a very long reproduction rate, and nature protection groups protests: cutting would change the environment far into the future. The requests for permission to cut these forests is in many cases still unsettled. To those areas which have been affected by deforestation belong the Tatra Mountains (Kopecka 2011).

Water in high mountains have been exploited in different ways. One of the most important is through hydropower. Hydropower is a form of energy which is sustainable since it does not rely on fossil fuels, coal, oil or gas, but large scale hydropower has often serious consequences for the mountain landscape, as some areas are flooded and others dried up, not the least because of the large reservoirs needed for the continued safe operation of the power plants plants (Photo. 1.1). Also the migration of fish is severely reduced by the

Photo. 1.1. The area above Suorva Dam - lake Kårtejaure and the stream Njabbejåkkå, Stora Sjöfallet National Park (https://en.wikipedia.org/wiki/Stora_Sj%C3%B6fallet_National_Park).

stations. Hydropower has been of decisive importance in many mountainous countries and was built early, mostly in the early 20th century. In Norway hydropower accounts for all electricity, in Sweden for 46% and in Finland (less mountainous) for 22%. The landscapes have thus been changed a long time ago. Present hydropower expansion is mostly due to the building of small stations which have very little impact on the landscape. In Sweden there are some 4000 small stations, mostly outside the mountains. The small stations are of importance in e.g. Germany and Latvia and under intense development (Rydén 2012b).

Many mountains areas have considerable mineral deposits and a developed mining industry. In North Sweden the Kiruna iron mine is the largest. Pit mining began at the site in 1898 and was followed by underground mining from 1960. Today it is the largest underground iron ore mine in the world. The state-owned mine is producing some 26 million tonnes of iron ore per year. Mining will continue for a considerable period as much is still left of the very large ore body of 4 kilometers length, 80–120 m thickness and depth of up to 2 kilometers. Further mines are found in the mountainous areas (Bergslagen) in mid Sweden.

Slovakia and Poland had a very important mining industry in their part of the Carpathian Mountains. However in this case most mines have been closed and are historical. Classical and well known mining places include Banská Bystrica once known for its abundant deposits of copper (and to a lesser extent of silver, gold, and iron), Kuźnice and Stare Kościeliska with iron (a leser extent of copper and silver), and Banská Štiavnica (silver, gold; today with a mining museum). During the communist period the Slovakian mining industry was still an important part of heavy industry and vital for the economy An uranium mine was operating a few years in the Polish Tatra Mountains (Biały creek valley). Today it is no longer competitive. The three universities with mining specialties: AGH (Academy of Mining and Metallurgy) in Krakow, Poland, the Technical University in Ostrava, Czech Republic and the Kosice Technical University, Slovakia, bear witness of the importance of the mining sector in the region (Rydén 2012a).

The efforts to open new mines have led to severe clashes between nature protection civil society groups and the mining companies. The arguments of the protesters, including the reindeer herding Saami, refer to the fact that mining can only be short term, but destroy the area for very long term, and thus is not at all sustainable. The companies usually refer to economic development and job creation and often get the local authorities to join. The only way to protect an area against mining is legal nature protection, decided on by the state authorities.

All exploitation of a mountains area requires access to the sites, hydropower stations and even more so mines. The roads may not take too large surface area but they are serious for the animal life as they constitute artificial borders right into their territories.

Wild life accidents are also increasingly common both on roads and railroads. The building of wind power stations is another infrastructure expansion now reaching mountainous areas. Their impact on biodiversity seem to mostly be a question for birdlife, as large birds of prey are unable to avoid the turning propeller blades of the stations, turning with very high speed. As wind power also is very disturbing for the landscape they are not popular among the visitors, a fact which may limit their growth.

Tourism in high mountain areas

The number of people visiting the European mountains for tracking, fishing, skiing, etc. is today dramatically high and increasing every year. It is also clear that the visitors are increasingly coming from all of Europe and not only the closest countries. It seems that an important aspect of the development of the rural areas of our region is to protect and make our mountains available for us and coming generations.

In Sweden, where detailed statistics is available, almost half of the 15–70 age population has visited the Swedish Mountains once or more times during 5 year, 25% has visited twice or more, and 20% three times or more, while only 0.5% live permanently in the area (Brouder 2014). The larger parts of the visits occur in the winter period for skiing and scooter driving. During summer touring in the *fjell* is dominating followed by fishing and canoeing. People spend time photographing, bird watching and in general enjoying outdoor life.

Commercially mountain tourism is important. Up to 67% of the visitors use a commercial facility for living, and meals (Rydén 2012a). It is obvious that tourism constitutes a considerable part of the economy of these areas. Employment is created in restaurants, cafés, hotels and hostels. During winter it is slalom slopes and lifts, leasing of skis and other equipment, which creates economy; during summer it is fishing cards, canoes etc.

Southern Poland's mountain areas bordering Poland, Czech Republic, Slovakia and Ukraine similarly have an important tourism industry. The main centre for visit to Polish Tatra Mountains, Zakopane, is visited by 2.7 million tourists every year, for touring, skiing and other activities (Photo. 1.2, Baścik et al. 2007). The Bieszczady Mountains to the west shared with Czech Republic is similarly very popular as is the Karkonosze Mountains with winter sports centres Karpacz and Szklarska Poręba, while the Carpathians in Ukraine has a growing number of visitors, not the least because of the cheap prices. More to the west and closer to the German border the Sudeten Mountains have a large number of very popular resorts, including spas, for visitors. Spas have a very long tradition from medieval times. People go to spas for health and social reasons. Popular spas include Krynica, Żegiestów and Piwniczna in Beskid Sądecki. Efforts are made to regulate tourism to trails and defined areas, a step important for the protection of biodiversity. In many cases tourists are simply too many and the landscape becomes worn out. Efforts to develop eco-tourism, with the goals to reduce the impact on wild life and landscape, is ongoing in many countries in the region.

Photo. 1.2. Mass tourism in the Tatra National Park affects negatively the natural environment (https://wiadomosci.onet.pl/kraj/kolejka-na-giewont/610nm).

Concluding remarks

It is obvious that many activities in mountain regions cannot avoid influencing or even counteracting each other. Thus the state as well as civil society need to take responsibility for balancing these conflicts and safeguarding that mountain regions can continue to play their important roles. This is also a crucial part of sustainable development. For this purpose the long term concerns needs to be given larger importance than the short term. In general giving mountainous areas efficient natural protection status should continue in order to safeguard biodiversity, a very threatened planetary resource. Such measures should be designed so that mountains visitors can continue to enjoy nature and wildlife, although within limits set by the sensitivity of each area. In general mining should be limited especially considering that it is not part of a recycling economy. Global warming and climate change is a destructive development, not only for mountainous areas but in general for the planet and its inhabitants. The changes needed to minimize its effects are those which we all should take for supporting sustainable development and a better future.

Chapter 2

High mountains in the Baltic Sea basin

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Abstract: The aim of the chapter is focused on high mountain regions in the Baltic Sea basin. High mountain environment has specific features defined by Carl Troll. The presence of timberline (upper tree line) and a glacial origin of landforms are considered as the most important features of high mountains. The Scandianavian Mountains and Tatra Mountains comply with the above definition of the high mountain environment. Both mountain chains were glaciated in Pleistocene: the Fennoscandian Ice Sheet covered the northern part of Europe including the Scandinavian Peninsula while mountain glaciers occurred in the highest part of the Carpathian Mountains.

Keywords: U-shaped valleys, glacial cirques, perennial snow patches, altitudinal belts

The Baltic Sea and its drainage basin – general characteristic

The Baltic Sea is one of the largest semi-enclosed seas in the world. The sea stretches at the geographic latitude almost 13° from the south to the north, and at the geographic longitude 20° from the west to the east. As a shallow epicontinental sea, it is cut off from the ocean having only a narrow connection with the Atlantic through the Danish belts (Skagerrak, Kattegat). The present connection with the North Sea was established 7000 years ago. The Baltic Sea is connected by artificial waterways to the White Sea *via* the White Sea Canal and to the German Bight of the North Sea *via* the Kiel Canal. The Baltic Sea is divided into the following units: Baltic Sea Proper, Bothnian Bay, Bothnian Sea, Gulf of Finland, Gulf of Riga, and Kattegat (Fig. 2.1). It is about 1300 km long, on average of 193 km wide, and an average of 55 m deep. The maximum depth is 459 m (Landsort Deep). The surface area is ap. 392,979 km^2 (without Kattegat), and the volume ap. 22,000 km^3. The periphery amounts 8100 km of coastline (Table 2.1, Andersen et al. 2006, Håkanson et al. 2003b).

The Baltic Sea occupies a basin formed by glacial erosion during three large inland ice ages. The latest and most important one lasted from 120,000 until ap. 18,000 years ago. The Baltic Sea underwent a complex development during last several thousand years after the last deglaciation. At present it exhibits a young

Table 2.1. Characteristics of the Baltic Sea (Andersen et al. 2006, Håkanson et al. 2003a, https://en.wikipedia.org/wiki/Baltic_Sea).

Attribute	Baltic Sea
Geographical latitude [°N]	53–66
Geographical longitude [°E]	10–30
Area (including Kattegat) [km^2]	415,266
Max. length [km]	1,601
Max. width [km]	600
Average depth [m]	52.3
Max. depth [m]	459
Water volume [km^3]	21,721
Approximate shore length	8,100
Average salinity [‰]	7
Drainage basin [km^2]	1,720,270

Fig. 2.1. The Baltic Sea basin (red line – the Baltic Sea watershed, background map from https://topotools.cr.usgs.gov/).

aquatic ecosystem. The Baltic Sea is a brackish water body of salinity 7–15‰, meaning that it is neither a fresh water, nor a fully marine water (a fully marine environment has salinity 35‰). The present conditions of low salinity prevail approximately in the last 3000 years. Winter ice cover makes the life conditions for fauna and flora difficult. The sea is rich in nutrients and it is polluted. There are following reasons why the Baltic Sea is a unique aquatic ecosystem (Håkanson et al. 2003a):

– it is large,
– very shallow,
– it is a sheltered inland sea with many coastal types,
– it has brackish water,
– it is located mostly in the cold climate,
– it has a heavily industrialized catchment area with a large population and intensive land use,
– it is sensitive to environmental impact,
– its pollution represents threat for people, flora and fauna.

These specific features of the Baltic Sea are influenced by the drainage area which spreads ap. 2500 km from the south (Carpathian Mountains) far to the north (Scandinavian Mountains). This long north-south extension causes differences in climatic conditions and a few climatic patterns occur there: transitional temperate warm, transitional temperate cool, continental, cool. The growing season in the far north is short (a polar day). The drainage area of the entire basin comprises 1,720,270 km^2, which is more than four times larger than the entire water area of 415,266 km^2 (Table 2.1). The area of 14 countries which are located in in the Baltic Sea basin represents about 15% of the area of Europe (Sweden, Finland, Russian Federation, Estonia, Latvia, Lithuania, Belarus, Poland, Germany, Denmark and small parts of Ukraine, Norway, and Slovak and Czech republics). The Baltic Sea basin is densely populated (85 million) and heavily industrialized. The main environmental challenges are eutrophication, heavy metals, dioxin, DDT, PCB, PAH and organic tin compounds, alien invasive species, deliberate illegal discharges from ships, growing risk of oil accidents from oil field exploitation and rapidly growing oil transport, as well as nuclear safety (Sundström, Andersson 2003).

The Baltic Sea basin is composed of a complex of geographical landforms with a high diversity over the area. The lowland (0–200 m a.s.l.) dominates and occupies 72.1% of the whole basin. Lowland spreads around the Baltic Sea forming a broad area of the forested lakelands. After the ice sheet melted away the land had been shaped to form a large number of lakes (lakes account for 6.1% of the whole Baltic Sea basin). The contribution of mountainous area elevated over 600 m a.s.l. accounts 4.3% and areas over 1000 m a.s.l. represent merely 0.6% (Table 2.2). There are following mountains in the Baltic Sea drainage basin: Scandinavian, Sudeten, Beskid, Pieniny, and Tatra. Despite their small share in the Baltic Sea basin, the mountains play a key role in the environment and human life (Rydén 2019). Noteworthy are the high mountains – areas of distinct environments with spectacular and specific features.

Table 2.2. Altitudinal belts in the Baltic Sea basin (calculated on the base of https://topotools.cr.usgs.gov/).

Altitude	Area	
	[km^2]	[%]
0–200	1,239,652.00	72.062
200–600	406,164.30	23.610
600–1000	63,666.15	3.701
1000–1500	10,098.03	0.587
1500–2000	646.51	0.038
2000–2600	42.56	0.002
Total	1,720,269.55	100.000

High mountains – what does it mean?

The geographical term "high mountains" has been strictly defined since the Carl Troll (1899–1975), a German geographer and botanist, was engaged in ecology and geography research of mountainous lands. He gave the main concepts and terminology of high mountains, therefore he may be called a pioneer in modern high-mountain geography. Troll developed some ideas of Alexander von Humboldt, especially on the three-dimensional character of climate (i.e. the change of climate by latitude, longitude and elevation) and its influence on the distribution pattern of altitudinal belts, vegetation belts, lifeforms and also on certain landforms (Holtmeier 2015). Timberline (tree line) position in a high-mountain landscape is the most conspicuous and ecologically very important vegetation boundary in most high-mountain landscapes. Troll expressed his scientific opinion in the paper entitled "High mountain belts between the polar caps and the equator: their definition and lower limit" published in *Arctic and Alpine Research* in 1973. High mountain landscape has the following features that distinguish it from other landscape types (Balon 2000, 2002; Kotarba, Migoń 2010; Kozłowska, Rączkowska 2009; Troll 1973):

- it rises above the upper forest limit and above Pleistocene snow line[1],
- it has a glacial origin, and hence also features, which do not exist in other mountains (e.g. glacial cirques, steep rocky crests, cirque lakes, glaciated rocky knobs, striated rock walls),
- its evolution is affected by the geomorphological processes that are specific only for high mountains, e.g. the periglacial ones,
- is characterized by a definite physiognomy: a mosaic-stripe structure, with highly differentiated units,
- it is a very dynamic system of landscape processes, mainly the geomorphologic ones,
- human impact is more limited there than in other areas.

These prerequisites for high mountain environment are fulfilled in the Baltic Sea drainage basin in the Scandinavian Mountains and Tatra Mountains.

[1] Refers to the altitude where the accumulation of snowfall equals ablation (called also equilibrium line).

Scandinavian Mountains

The Scandinavian Mountains run through the Scandinavian Peninsula and form the second longest mountain range in Europe (after the Ural Mountains). They occupy the western and northern part of the Fennoscandia Peninsula, stretch by a strip up to 200 km wide and 1700 km long, in the territory of Norway, Sweden and partly in Finland. Along its central part, mountain height is strongly variable with peaks higher than 2100 m a.s.l. only in south central Norway and in northern Sweden. Mountain height is particularly low in the southernmost and northernmost parts, but also relatively low in the central parts. The southern part of the Scandinavian Mountains is broader and consists of a series of plateaux and gently undulating surfaces that hosts scattered *inselbergs* (Rudberg 1969). It contains Galdhøpiggen (2469 m a.s.l.) in Norway – the highest peak in the Scandinavian Mountains (Jotunheimen range), whereas Kebnekaise located in Swedish Lapland about 150 km north of the Arctic Circle is the highest peak of the Scandinavian Mountains within the Baltic Sea basin. Areas elevated over 1500 m a.s.l. represent 0.3‰ (ap. 540 km^2) of the Scandinavian Mountains in the Baltic Sea basin (Fig. 2.2, Table 2.3, Photo. 2.1).

The Kebnekaise massif has two main peaks, of which the southern, glaciated one had the altitude of 2097.5 m a.s.l. in August 2014. There are Kebnepakte, Isfalls, and Stor glaciers flowing towards the Tarfala valley (to the east), Björlings glacier flowing to the southeast, and Rabots glacier flowing to the west, plus several smaller glaciers throughout the area (Fig. 2.3; Photos. 2.1, 2.2). The northern peak is 2096.8 m a.s.l. high and it is free of ice. By August 2018, due to record heat, glacier on the southern peak had melted so that the northern peak is now the highest (Anderson 2018).

The Scandinavian Mountains were formed in the Caledonian orogenesis as a result of the closure of the Paleozoic Iapetus. They were several times unevenly raised, and eventually uplifted at the turn of the Silurian and Devonian periods. The Scandinavian Mountains are mostly built of crystalline and metamorphic pre-Cambrian rocks, and Ediacaran (Vendian), Cambrian, Ordovician and Silurian-aged sedimentary rocks. Natural resources include iron

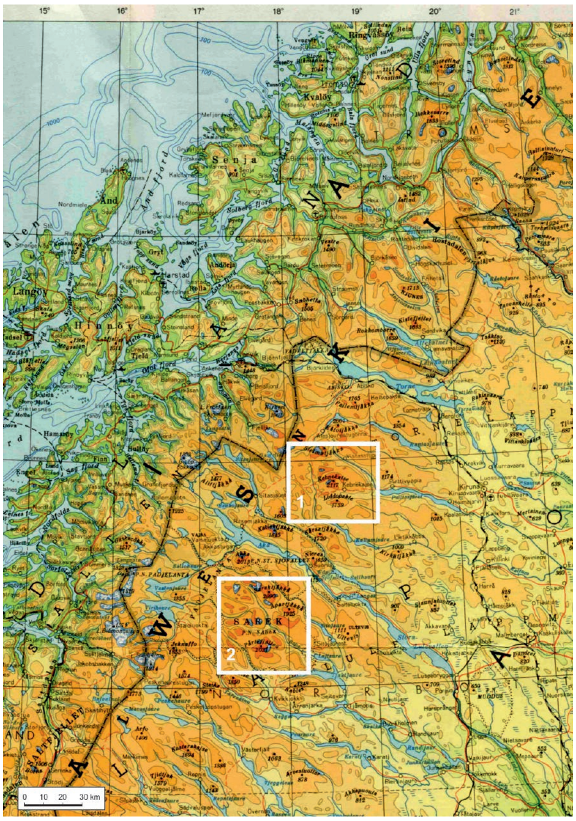

Fig. 2.2. The highets parts of the Scandinavian Mountains within the Baltic Sea drainage basin (1 – Kebnekaise, 2 – Sarek; details in Figure 2.3; based on Mapa… 1970).

Table 2.3. Characteristics of the Scandinavian Mountains within the Baltic Sea drainage basin (Nesje et al. 2008, https://topotools.cr.usgs.gov/).

Attribute	Scandinavian Mountains
Water divide	North Sea, Norwegian Sea, Barents Sea, Baltic Sea
Area over 600 m a.s.l. [km^2]	ap. 70,000
Length [km]	1700
Width [km]	up to 300
Highest peak [m a.s.l.]	Kebnekaise 2096.8
Timberline [m a.s.l.]	1300 – south, 200 – north
Glaciers	yes
Perennial snow patches	yes
Permafrost	yes

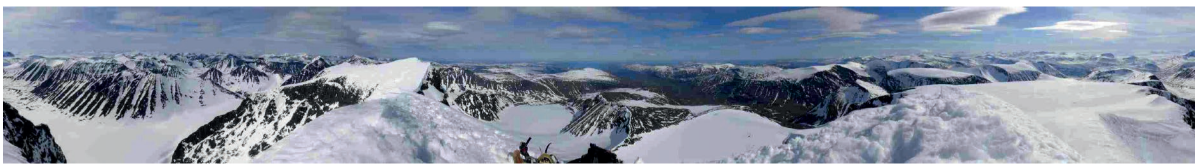

Photo. 2.1. Kebnekaise massif in the Scandinavian Mountains (https://en.wikipedia.org/wiki/Kebnekaise).

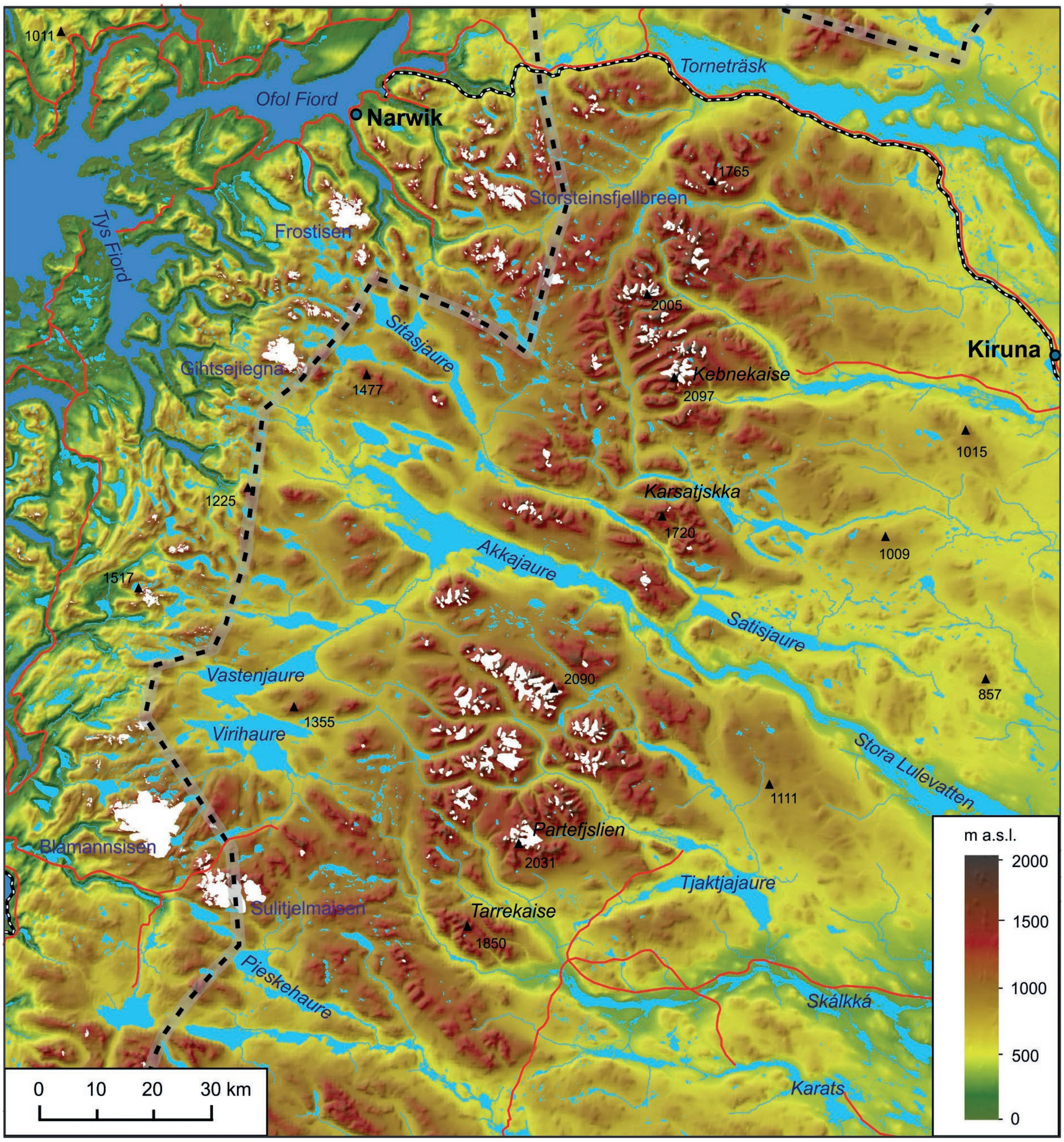

Fig. 2.3. Northern part of the Scandinavian Mountains with Kebnekaise – north of Akkajaure lake (based on https://topotools.cr.usgs.gov/).

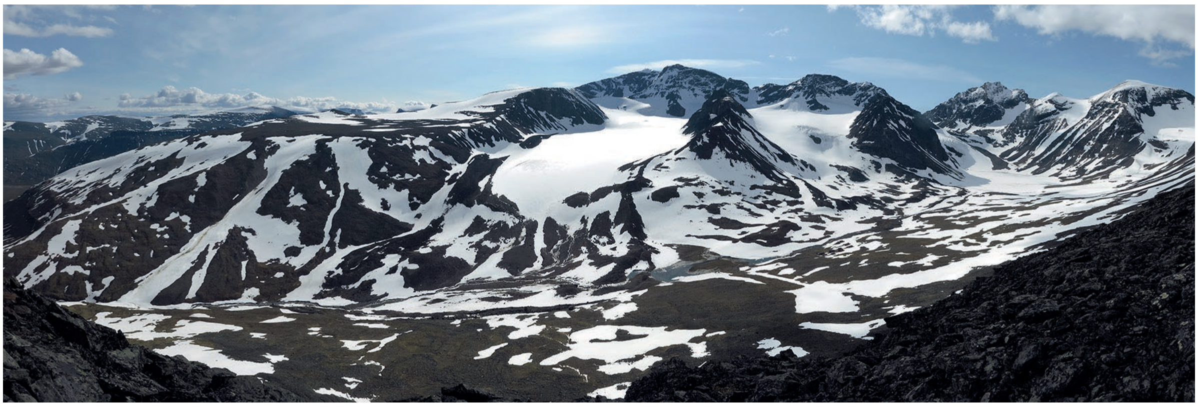

Photo. 2.2. Glaciers over the Tarfala valley in Kebnekaise massif (https://en.wikipedia.org/wiki/Tarfala_Valley).

(Kiruna), as well as copper, zinc and lead, nickel, molybdenum. During half of the last 2.75 million years the Scandinavian Mountains hosted mountain-centered ice caps and ice fields. During the Last Glacial Maximum all the Scandinavian Mountains were covered by the Fennoscandian Ice Sheet (in the same time mountain glaciers were in the Tatra Mountains). Recession of the ice sheet margin led the ice sheet to be concentrated in two parts, one part in southern Norway and another in northern Sweden and Norway. This time the Scandinavian Mountains has been sculpted by glacial erosion. There are U-shaped valleys, glacial cirques – at some locations coalesced cirques form *arêtes* and pyramidal peaks forming an "alpine topography" (Photo. 2.3; Lundqvist et al. 2011, Stupnicka 1978).

Glacial activity is marked strongly in the western part of the mountain chain where drowned glacier-shaped valleys constitute the fjords of Norway. In the eastern part of the mountain chain reshaped by glaciers, numerous mountain summits contain blockfields which escaped glacial erosion either by having been nunataks. Bare rock surfaces are common, mountain slopes are mantled by deposits of glacial origin including till blankets, moraines, drumlins and glaciofluvial material. It is interesting that distribution of "alpine topography" in the Scandinavian Mountains does not relate to altitude: for instance cirques in southern Norway can be found both near sea level and at 2000 m a.s.l. Most cirques are found between 1000 and 1500 m (Hall et al. 2013, O'Dell 1961).

Due to a considerable meridional extent, the Scandinavian Mountains lie in three climatic belts: moderate warm in the south, moderate cold (central areas) and polar (in the north). The mountain range plays a role of a topographic barrier for wet air masses influenced by the Golf Stream: precipitation totals reach 3500 mm per year on the western side of the mountains and 400 mm on the eastern side (precipitation shadow). Due to high precipitation and low snow line position (ap. 700 m a.s.l. in the southern part of the mountains), the Scandinavian Mountains are the most glaciated area in Europe. Field glaciers and outlet glaciers are typical for the Scandinavian Mountains. There are also valley glaciers. The mountains are headwaters of most major Scandinavian rivers as: Torne, Kalix, Lule, Skellefte, Ume, Angerman, Indal, Ljungan, Ljusnan, Dal and Klarälven (Fig. 2.1). Steep river channels and weakly diversified river discharge variability throughout the year favor use of water energy by power plants. There are numerous postglacial lakes with elongated SE-NW oriented shoreline (Photo. 2.4; Nesje et al. 2008; Mydel, Groch 2000, Trepińska 2002).

There are variations in timberline elevation in the Scandinavian Mountains: from a maximum height of 1300 m a.s.l. in the southern part to ap. 200 m a.s.l.

Photo. 2.3. The mountain Pierikpakte in the Äpar massif with "alpine topography", Sarek National Park (https://en.wikipedia.org/wiki/Sarek_National_Park).

Photo. 2.4. The lake Torneträsk located in the tectonic valley – Torne river outflows from the lake into the Baltic Sea (Photo. J. Siwek).

in the northern part of the mountains. Lower parts of the mountains are covered with mixed forest in the south and coniferous forest in the north. The mountain birchwood (*Betula pubescens*) spreads over forest zone. Above this lies a narrow belt of willow shrub and above a belt consisting of meadow with herbs, grass, and heath. Peat bogs and mires are common in the depressions. The highest parts of the mountains is a glacial zone. Tundra communities (dwarf shrubs, sedges and grasses, mosses, and lichens) are typical for the northern part of the mountains (Odland 2015, Podbielkowski 2002).

There are numerous national parks in the Scandinavian Mountains with typical alpine landforms, i.a. Sarek, Padjelanta, Stora Sjöfallet, Abisko.

Tatra Mountains

The Tatra Mountains are the highest mountains of the entire Carpathian Mountains (Photo. 2.5). The Carpathian Mountains form the third longest mountain range in Europe (Fig. 2.4). They begin near the Danube river at the border of Austria and Slovakia, stretch to the north-east (Czech Republic, Hungary, Slovakia, Poland – the Western Carpathian Mountains), then turn to the east (Poland, Slovakia, Ukraine – the Eastern Carpathian Mountains) and south (Romania, Serbia – the Southern Carpathian Mountains) to end at the borders of Romania and Serbia. The entire mountain range is over 1500 km long and occupies the area of 209,000 km^2. Except the Tatra Mountains, another high part of the Carpathian Mountains, with the highest peaks exceeding 2500 m a.s.l., is in Romania (the Fagaras, Parang, Retezat and Bucegi mountains). The Carpathian Mountains are geologically young. They were formed during the Alpine orogeny in upper Mesozoic and Tertiary, together with mountain ranges like the Alps, Caucasus, Pyrenees, Rocky Mountains or Himalayas.

The Tatra Mountains (Fig. 2.5) are divided into the Western Tatra Mountains and Eastern Tatra Mountains (composed of the High Tatra Mountains and Belianske Tatra Mountains). They are located in northern Slovakia (about 78% of the area) and southern Poland

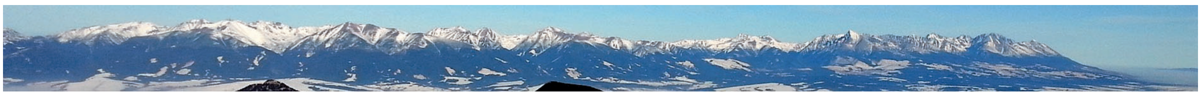

Photo. 2.5. The Tatra Mountains from the south: the Western Tatra Mountains on the left and in the center, the High Tatra Mountains on the right. The right edge of the photo shows a pronounced elevation gradient between the mountains and the neighbouring foothills. The dark belt below the snow zone shows forests dominated by Norway spruce (*Picea abies*, Photo. L. Holko).

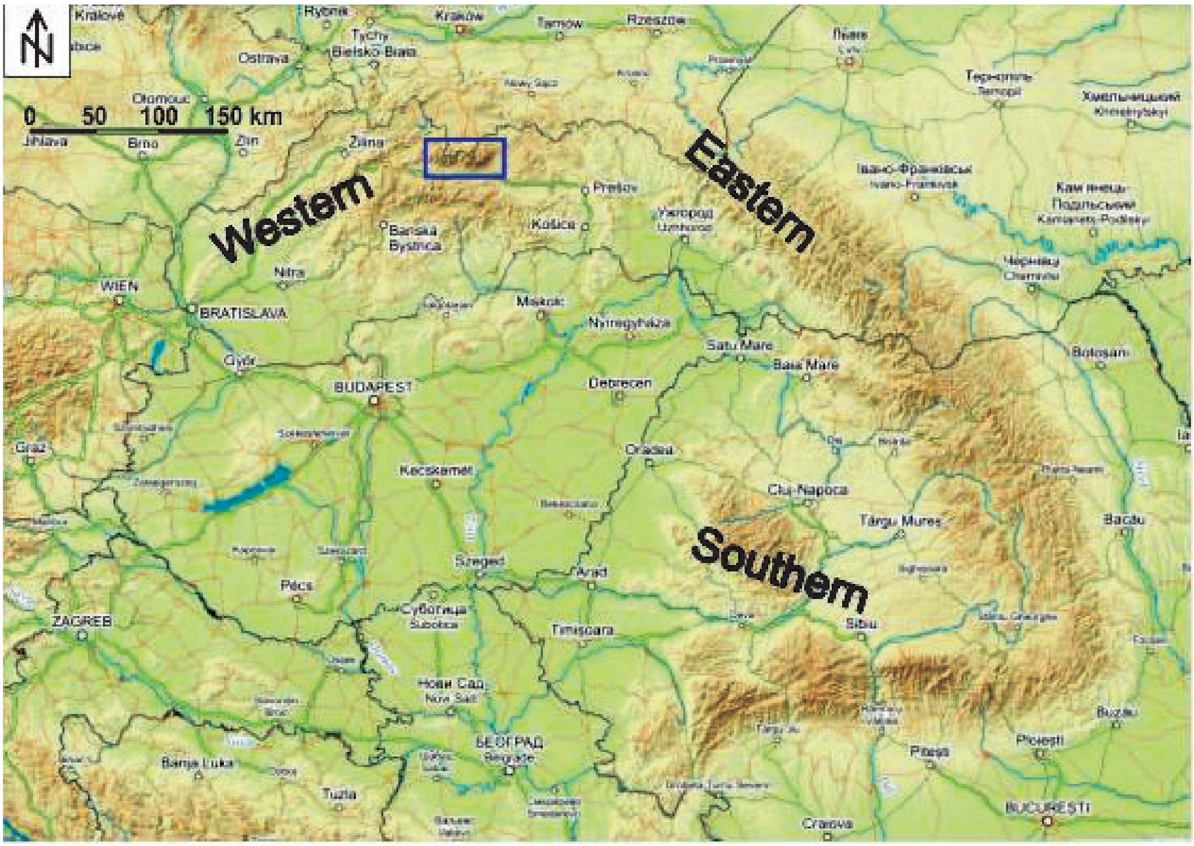

Fig. 2.4. The Carpathian Mountains, the rectangle shows the Tatra Mountains (based on www.mapy.cz).

(about 22% of the area). The mountain range is about 57 km long and about 18.9 km wide (Kondracki 1998). The Tatra Mountains represent the only part of the Carpathian Mountains that has a larger-scale rocky high alpine landscape. Despite their relatively small area of 785 km^2, the mountains represent a remarkable landscape.

The highest peaks of the Tatra Mountains are not located on the main ridge, but on the southern branches, i.e. Gerlachovský *štít* (2655 m a.s.l.) and Lomnický *štít* (2634 m a.s.l.) in the High Tatra Mountains, and Bystrá (2248 m a.s.l.) and Jakubiná (2194 m a.s.l.) in the Western Tatra Mountains. Gerlachovský *štít* and Lomnický *štít* are the highest peaks of the entire Carpathian Mountains, wherein the first one is the highest peak in the Baltic Sea drainage basin (Table 2.4).

Table 2.4. Characteristics of the Tatra Mountains within the Baltic Sea drainage basin (Hess 1965, Kondracki 1998, Mapa… 1970).

Attribute	Tatra Mountains
Water divide	Black Sea, Baltic Sea
Area [km^2]	785
Length [km]	57
Width [km]	up to 18.5
Highest peak [m a.s.l.]	2655 (Gerlachovský *štít*, Slovakia)
Timberline [m a.s.l.]	1550
Glaciers	no
Perennial snow patches	yes
Permafrost	no?

The geological structure of the Tatra Mountains is typical of mountains with alpine folding. They started to rise in lower Neogene. They are mainly formed by crystalline rocks (schist, paragneiss, migmatite) and granodiorite. Mesozoic rocks (dominated by limestone and dolomite) occur along the western, northern and eastern boundaries (Passendorfer 1983). Present relief was significantly influenced by the Pleistocene glaciation that left the U-shaped valleys, series of cirque basins and knife-edged *arêtes*, and glaciofluvial and fluvioglacial sediments (Lukniš 1973). During the Last Glacial Maximum the Tatra Mountains were covered by 55 valley and cirque glaciers, which occupied an area of 279.6 km^2. The average thickness of ice amounted 88 m. There was an asymmetry of glaciation: the southern slopes were occupied by glaciers longer than on the northern slopes. It was caused by the asymmetry of topography: the southern facing valley heads were located at higher elevation compared to the northern facing

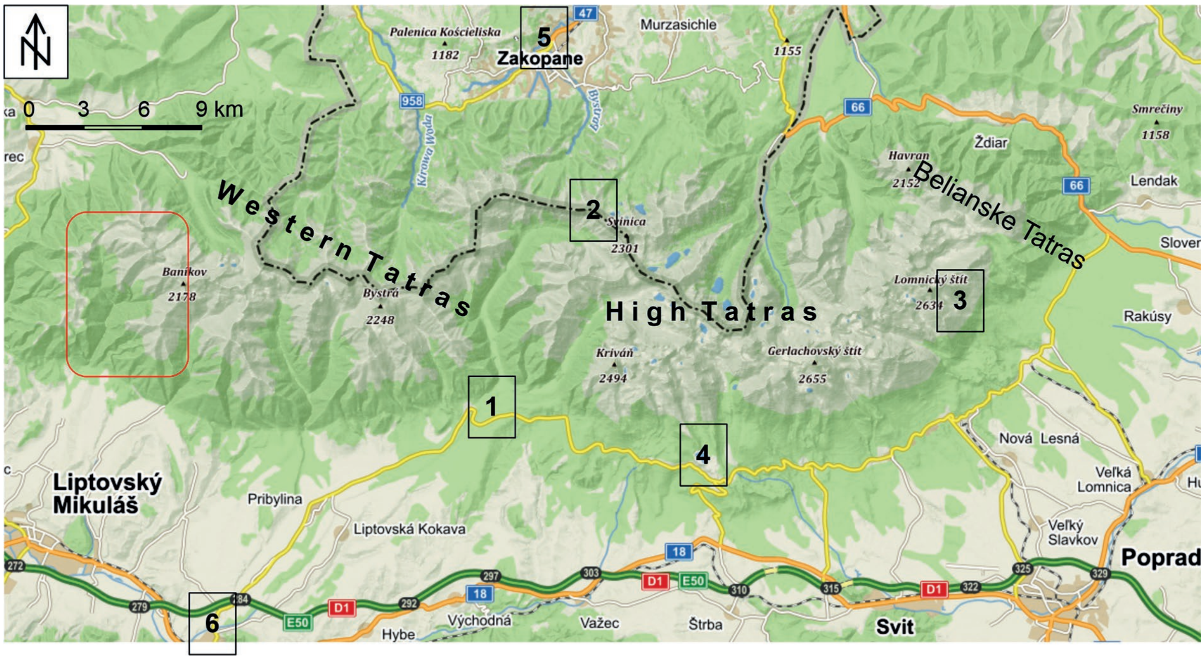

Fig. 2.5. The Tatra Mountains (based on www.mapy.cz). The rounded rectangle on the left marks the Jalovecký Creek research catchment (area 22.2 km^2, mean elevation 1500 m a.s.l.); 1 – gauge on the Belá river (Podbanské) which has the longest record of annual runoff among the small mountain catchments of the Tatra Mountains (since 1895); 2 – the high mountain meteorological station Kasprowy Wierch (Western Tatra Mountains, 1991 m a.s.l., windward position, established in 1937); 3 – the high mountain meteorological station Skalnaté Pleso (High Tatra Mountains, 1778 m a.s.l., leeward position, established in 1939); 4 – meteorological station Štrbské Pleso (High Tatra Mountains, 1354 m a.s.l., leeward position, established in 1902); 5 – meteorological station Zakopane (the foothills, 855 m a.s.l., windward position, regular data since 1911); 6 – meteorological station Liptovský Hrádok (the foothills, 640 m a.s.l., leeward position, established in 1881).

slopes (Photo. 2.6). The higher altitude ice-surfaces favored bigger alimentation rate for southern glaciers. There are about 300 postglacial lakes (mostly in the High Tatra Mountains on the southern slope) that cover about 0.41% of the Tatra Mountains (3.23 km^2). Cirque, bedrock-moraine dammed, inter-sheepback, and moraine lakes prevail (Photo. 2.7). Eight of lakes exceed an area of 0.1 km^2 (Klimaszewski 1988, Kłapyta et al. 2016; Molnár, Pacl 1988).

The Tatra Mountains are located in a transitional position of the temperate climate influenced by polar oceanic air-masses from the west and polar continental air-masses – in the minority – coming from the east and north-east (Trepińska 2002). Rapid pressure changes and temperature inversions are typical for the Tatra Mountains. The annual air temperature ranges from 6°C in the lowest climatic belt to ap. −4°C in the fell belt. In spite of relatively favorable climatic conditions there are no glaciers due to lack of suitable orographic conditions (too steep mountain slopes, rocky walls). Perennial snow patches and firn-ice patches – an embryonic form of glaciers called *glacieret* – occur in shady places. They accumulate snow avalanches and wind-blown snow (Gądek 2011, Photo. 2.8).

Vegetation belts are well-developed in the Tatra Mountains. The forest belt spread to an elevation

Photo. 2.6. The northern facing slopes of the Tatra Mountains at the time of snowmelt season in May 2014 (Photo. J. Pociask-Karteczka).

Photo. 2.7. The High Tatra Mountains – the Czarny Staw pod Rysami and Morskie Oko lakes (Photo. A. Śliwiński).

Photo. 2.8. Perennial snow patches in the Tatra Mountains late summer (Photo. J. Pociask-Karteczka).

1550 m a.s.l. and is dominated by spruce. The sub-alpine belt between 1500 and 1800 m a.s.l. is covered by continuous or sparse dwarf mountain pine (*Pinus mugo*) which is replaced by mountain alpine meadow at the elevation of 1880 m a.s.l. The uppermost periglacial belt of rock faces, rock debris and locally permanent snow patches lies over the altitude 2300 m a.s.l. (Kotarba 1992).

Most of the area of the Tatra Mountains, both in Slovakia and Poland, is protected in national parks (the Tatranský národný park since 1949 and the Tatrzański Park Narodowy since 1954).

Comparison and conclusions

The Scandinavian Mountains and Tatra Mountains are the only regions representing the high mountain environment in the Baltic Sea drainage basin. There are water divides in both regions: the water divide of the North Sea, Norwegian Sea, Barents Sea and Baltic Sea in the Scandinavian Mountains, and the Main European Water Divide of the Black Sea and Baltic Sea in the Tatra Mountains. Gerlachovský *štít* – the highest peak of the Tatra Mountains – is located within the Baltic Sea drainage basin while Galdhøpiggen – the highest peak of the Scandinavian Mountains – lies out of the Baltic Sea drainage basin (in the Norwegian Sea drainage basin), and Kebnekaise (2096.8 m a.s.l.) is the highest peak of the Scandinavian Mountains within the Baltic Sea drainage basin.

The snow line in the Tatra Mountains is located much higher than in the Scandinavian Mountains due to the difference in geographic latitude. Presence of glaciers in the Scandinavian Mountains and their absence in the Tatra Mountains represents the essential difference between these two mountain chains. Glaciation consists of ice fields with outlet glaciers, which appear with fjords on the western slope, and deep valleys with long lakes and wetlands on the eastern slope of the Scandinavian Mountains. There are barely perennial snow and firn-ice patches in the Tatra Mountains located in shady, leeward deep sites (also below the snow line). There are numerous landforms and lakes which are evidences of the Pleistocene glaciation in the Tatra Mountains (U-shaped valleys, glacial cirques, *arête*, steep rocky crests, cirque lakes). Permafrost is an exclusive feature of the Scandinavian Mountains (the northern part) while its presence has not been proven in the Tatra Mountains. Altitudinal belts (i.a. vegetation, climate) are typical in both regions. There is a dwarf pine belt over the forest belt in the Tatra Mountains while the montane birch forest and tundra communities are typical for the Scandinavian Mountains.

In spite of dissimilarities in abiotic and biotic components of natural environment of these two mountain ranges, the high mountain landscape – common in both regions – makes them spectacular and exceptional.

Chapter 3

Hydrology of the Tatra Mountains – local and regional significance

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Abstract: The Tatra Mountains is the highest mountain range of the Carpathian Mountains. Despite their relatively small area of 785 km^2, the mountains represent a remarkable landscape element and are the regional "water tower" of northern Slovakia and southern Poland. They are also some of the most attractive and beloved places in both countries. The objective of this contribution is to provide information on the history of meteorological and hydrological measurements on this territory and present the summary knowledge of the hydrological cycle obtained from standard and research networks.

Key words: "water tower", water balance and its components, Carpathian Mountains

INTRODUCTION

The first hydrographic descriptions of the Tatra Mountains come from the 17th century. The early descriptions focused more on lakes than on rivers (Pacl 1973, Szaflarski 1972). The earliest limnological measurements were carried out by Jakub Buchholtz (1696–1758) who measured the water level in the Nižné Temnosmrečinské lake intending to disprove the theory about connection of the lake with the sea. The big flood of 1813, described by Swedish botanist G. Wahlenberg who was then in the Tatra Mountains, resulted in deeper interest in rivers. Hydrographic service on the territory of present-day Slovakia was established in the second half of the 19th century. The first gauge in the area of the Tatra Mountains (Studený Creek/ Oravský Biely Creek) was installed in 1920. The gauge in the Poprad River at Matejovce was installed in 1921. The gauges on the Biely Váh River at Východná and the Belá River at Podbanské have been in place since 1922 and 1924, respectively. Other 10 gauges were installed before 1938. The network expanded in 1940–1944 by 8 gauges and in 1946–1960 by other 7 gauges (all above information by Pacl, 1973). Pekárová et al. (2005) and Pekárová and Pekár (2007) extended the annual runoff data series for the Belá River at Podbanské by regression analysis back to the year of 1895.

Regular meteorological data that allow quantitative assessment of the water balance in the Tatra Mountains are measured for about a century. An overview of the history of meteorological measurements in the Tatra Mountains region was presented e.g. by Šamaj (1973). He reported that the first meteorological measurements (air temperature) in the High Tatra Mountains and their vicinity were made in the 1720s. The oldest preserved observations were from years 1789––1800. Systematic measurements have been archived since 1873. Meteorological measurements in Starý Smokovec started in 1875 and similar meteorological station was established in 1881 in Liptovský Hrádok. Stations in Tatranská Lomnica, Poprad, and Štrbské Pleso (all in Slovakia) were established at the turn of the 20th century. The network substantially expanded in the 1920s when 15 new stations started to operate. Important high mountain stations were established between 1936 and 1940 at Kasprowy Wierch (Poland, Western Tatra Mountains) and at Skalnaté Pleso and Lomnický *štít* mountain (Slovakia, High Tatra Mountains, Fig. 2.5).

The Tatra Mountains – a "water tower" of Central Europe

From the Himalayas in Asia to the Alps in Europe, and the Rockies in North America, high mountains are all important sources of water to people living downstream. The Tatra Mountains are the highest mountain range of the Carpathian Mountains. They form part of the European water divide between the Black Sea and the Baltic Sea. The Tatra Mountains can be called a natural "water tower" of Central Europe. They are vital headwaters of the significant tributaries of major rivers in this region: Danube and Vistula. They give birth to Vah – the left tributary of Danube and Dunajec – the right tributary of Vistula. Freshwater from rain and melting snow feeds streams, lakes and eventually ends in the Black Sea or Baltic Sea (Fig. 3.1).

Freshwater of high mountains also replenishes aquifers. The Tatra Mountains are the recharge area for the Podhale basin – a hydrogeological structure built of two units: Mesozoic (Triassic-Cretaceous) and Tertiary (Palaeogene) formations (Fig. 3.2). Mesozoic formations are underlain by Palaeozoic formations (crystalline rocks). The crystalline and sedimentary Tatra Mountains massif adhers to the Podhale basin. Precipitation water infiltrates to the sedimentary rocks in the Tatra Mountains and percolates deep within the Mesozoic unit. Triassic carbonates and Jurassic sandstone and carbonates are the main water aquifers. All of them are confined aquifers. The Podhale geothermal aquifers are isolated from the atmospheric impact by semi-permeable Jurrasic and Cretaceous mudstone, siltstones, shales.

The most valuable groundwater resources exploited from the second half of the 20th century occur within the Middle Eocene Nummulitic limestone and carbonate conglomerates. These formations occur over the entire Podhale basin and spread out to Slovakia (Chowaniec 2009, Małecka 2003). The depth of aquifer with water of temperature 80–95 °C is 1–3.5 km. The Podhale basin has been recognized as a hydrogeothermal province of high importance. Regional geothermal project started there in the end of the 1980s and successively a great regional heating system was developed in Zakopane. Contemporary, the geothermal energy provides a supply of clean, environment-friendly domestic heating in the Podhale region and serves for balneological and spa purposes both in Poland and Slovakia.

Water balance

Annual precipitation in the Tatra Mountains area varies from 600–800 mm in the foothills to more than 2000 mm in the mountains. Maximum seasonal precipitation occurs in summer, minimum in winter. Second, smaller precipitation maximum is sometimes observed in autumn. Snow cover is typically present in the mountains between November and May. About 60–80% of annual precipitation runs off. The long-term mean annual specific runoff is 40 to 50 $l \cdot s^{-1} \cdot km^{-2}$ (Pociask-Karteczka et al. 2010). Annual runoff maximum occurs in spring months. It is related to snowmelt accompanied by rainfall in late April and May (when most of the snow cover is already melted). Annual runoff minimum occurs in winter (January, February).

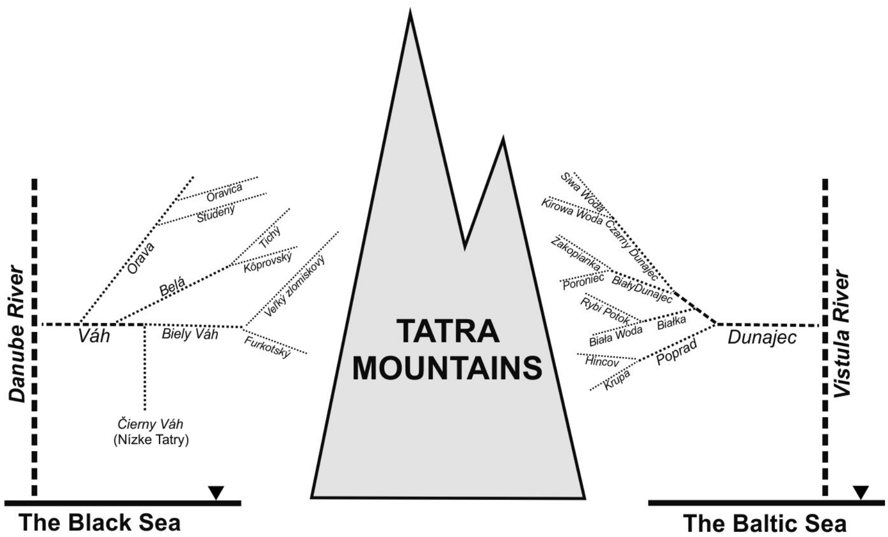

Fig. 3.1. The Tatra Mountains as the "water tower" of Central Europe.

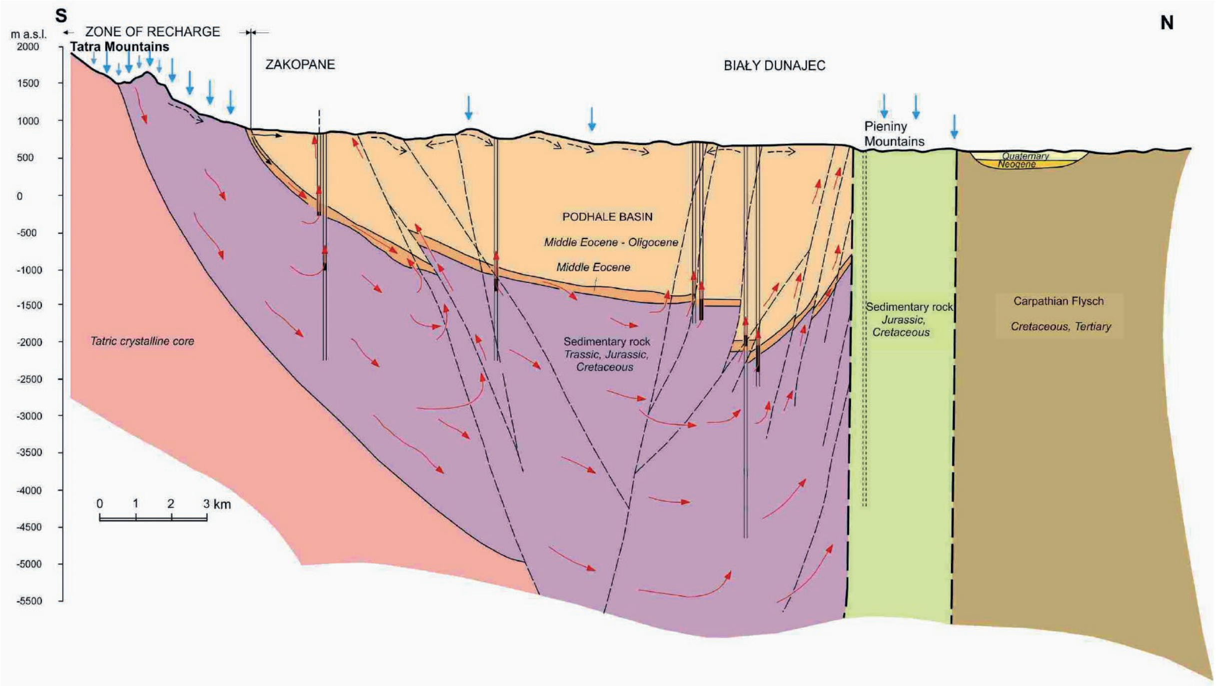

Fig. 3.2. A cross section of the Podhle basin; blue arrows indicate precipitation, red arrows indicate groundwater circulation (Chowaniec 2009, simplifed).

An example of seasonality in catchment precipitation and runoff from the catchment on the southern slopes of the Western Tatra Mountains is shown in Fig. 3.3.

Owing to their geographical position in Central Europe, the Tatra Mountains act as a barrier to the precipitation – bringing air masses coming from the north-west and west. As a result, the pronounced windward and leeward effects are observed on the northern and southern slopes of the mountains (Fig. 3.4). Northern slope has more precipitation and steeper altitude gradients of annual precipitation. Catchments located on the northern side of the mountains have higher runoff (Fig. 3.5). Fig. 3.5 provides also the information on annual precipitation (point values), catchment runoff and typical size of mountain catchments of the Tatra Mountains.

Hydrological processes – the Jalovecký Creek catchment

Klemeš (1990) noted that "in spite of their hydrological importance, mountainous areas represent... some of the blackest black boxes in the hydrological cycle" owing to "harsh environment, inaccessible terrain, the high variability of topography, soils, vegetation, temperature distribution, radiation and albedo, deposition and melting of snow and ice, turbulent character of mountain streams, rapidity of changes in atmospheric conditions, etc." Systematic research of hydrological cycle based on good data can contribute to the improvement of the knowledge of hydrological cycle in these areas which "control much of the distribution of atmospheric moisture over the continents" (Klemeš 1990). Such a systematic research is carried out in the Tatra Mountains since the end of the 1980s in the mountain part of the Jalovecký Creek catchment. This chapter presents a brief summary of the obtained knowledge on the hydrological cycle from precipitation to catchment runoff.

The Jalovecký Creek catchment is a small mountain catchment located in the Western Tatra Moutains and in the adjacent Liptovská kotlina Valley. Jalovecký Creek is the right-hand tributary of the longest Slovak river Váh. Area of the entire Jalovecký Creek catchment is ap. 46 km^2, and its elevation ranges from 560 to 2178 m a.s.l. The catchment is composed of two distinctly different parts. The mountain part of the catchment (area 22.2 km^2, mean elevation 1500 m a.s.l., elevation range 820–2178 m a.s.l., mean slope 3.00°) is located in the Western Tatra Mountains. It is dominantly built by crystalline rocks (schist, paragneiss, migmatite) and granodiorites that account for 48% and 21% of the area, respectively. About 7% of the mountain part is composed of nappes formed by Mesozoic rocks (mainly limestone and dolomite). Quarternary sediments (slope sediments and moraines) cover about 24% of the mountain part of the catchment. Land use is represented by forests (main-

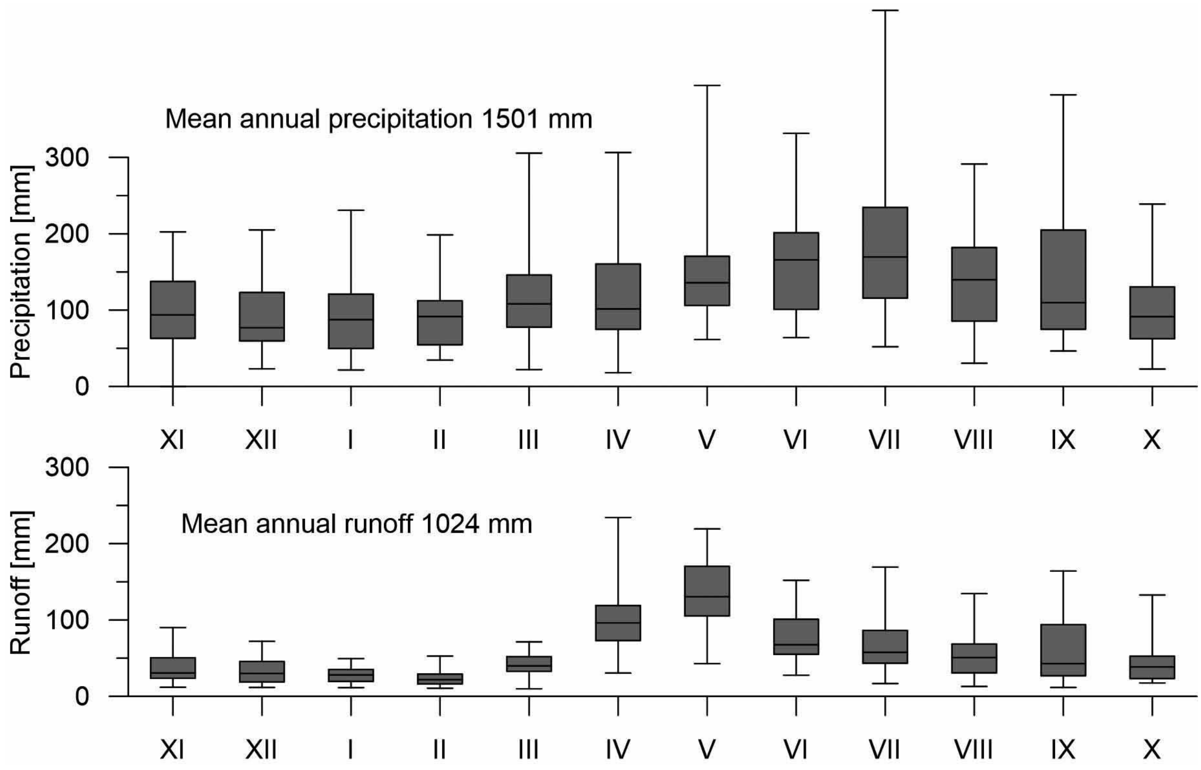

Fig. 3.3. Monthly precipitation and runoff in the Jalovecký Creek catchment (the Western Tatra Mountains) during a hydrological year (November–October); data from hydrological years 1988–2017; the boxplots represent maximum, third, second and first quartiles and minimum (Holko, Danko 2018; modified).

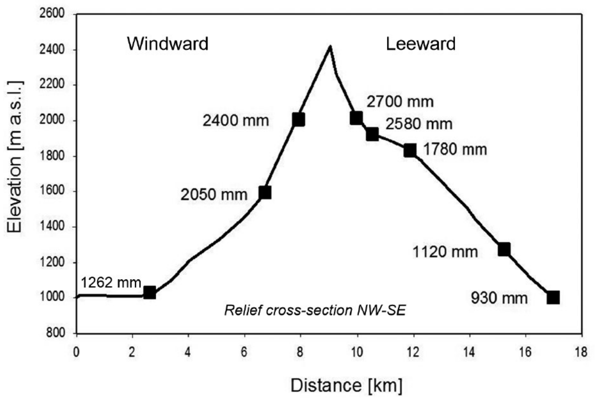

Fig. 3.4. Mean annual precipitation on the wind- and leeward slopes of the High Tatra Mountains (Molnár, Pacl 1988; modified).

ly spruce), dwarf pine and alpine meadows and rocks that cover 44%, 31% and 25% of the area, respectively. The mean annual precipitation and runoff are 1501 mm and 1024 mm, mean annual air temperature at 1500 m a s.l. is 3.0°C. Most hydrological research is focused on this part of the catchment. The foothill part of the catchment (about 24 km^2, mean elevation 806 m a.s.l., elevation range 560–1606 m a.s.l.) is located in the Liptovská kotlina valley. It is built mainly by sedimentary rocks of Paleogene covered by the alluvium of the Jalovecký Creek. The land use in this part of the catchment is dominated by agricultural land (fields, grasslands) and several small urbanized areas. Mean annual precipitation in the foothill part is 806 mm, mean annual air temperature at 750 m a.s.l. (close to the outlet of the mountain part of the catchment) is 6.2°C. Two stations providing meteorological data (at 750 and 570 m a.s.l.) are located in this part of the catchment. Detailed information about the measurement network is given i.a. in Holko and Danko (2018).

Spatial distribution of precipitation shows clear difference between the mountains and foothills; precipitation amounts in the mountains depend more on the position of the gauge than on its altitute (Fig. 3.6). The number of precipitation days in the mountains is not much greater than outside them (mostly by up to 5 days). However, when it rains, daily precipitation totals in mountains are greater than in the foothills (Fig. 3.7). Daily precipitation totals in the foothils are most frequently below 10 mm (about 80% of days with precipitation). In mountains about 20% of days with precipitation has daily precipitation amount between 20 and 30 mm (Table 3.1). Hourly data indicated that

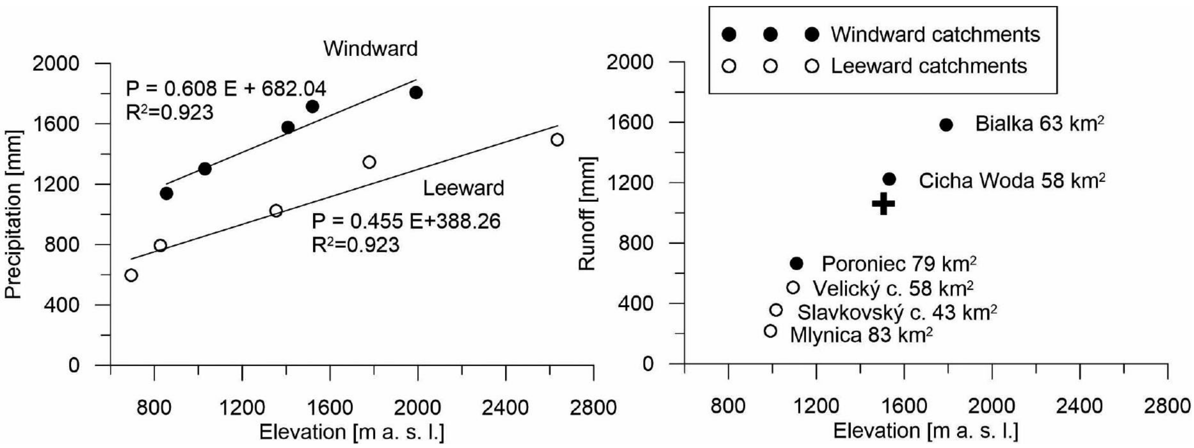

Fig. 3.5. Elevation gradients in the long-term mean annual precipitation (left) and catchment runoff (right; most catchments are located in the High Tatra Mountains) on the wind- and leeward slopes of the Tatra Mountains; data from 1961 (1963) – 2010; numbers near catchments' names show catchments areas; the cross symbol in the left panel indicates the Jalovecký creek catchment (data from 1988–2017) which has both wind- and leeward slopes (Górnik et al. 2017, modified).

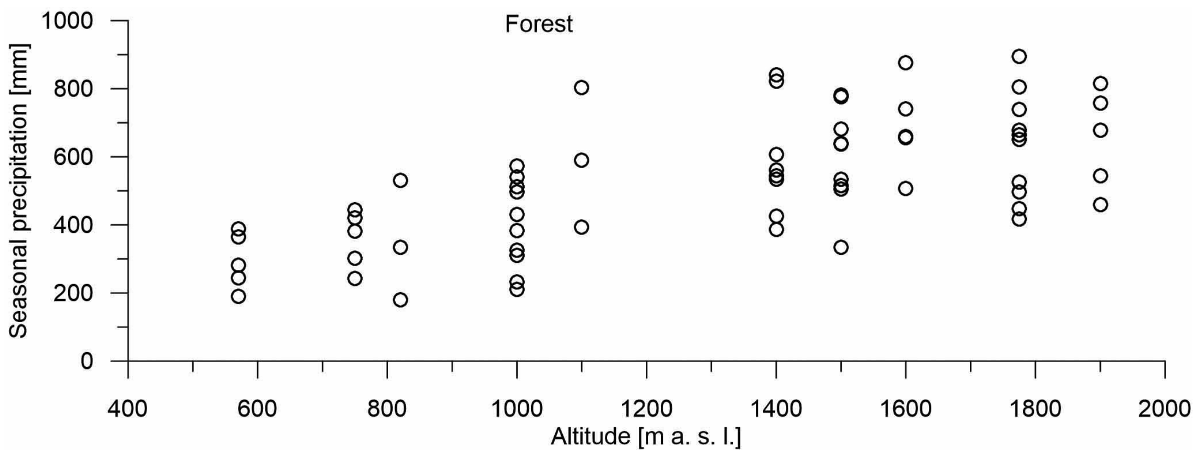

Fig. 3.6. Summer precipitation (June to September 2013–2017) in the foothill (up to 820 m a.s.l.) and mountain parts of the Jalovecký Creek catchment (Holko, Danko 2018; modified).

when it rains, the rain usually hits entire catchment (22 km^2). In other words, at the typical scale of a small mountain catchment of the Tatra Mountains, the runoff events which are caused by precipitation occuring only in part of the catchment are rare (Holko et al. 2015a).

Spruce dominated forest covered about 44% of catchment area before the onset of changes that started approximately in 2012 as a result of windfalls and consequent bark beetle outbreaks. Spruce interception represents about 30% of precipitation on the longer-term scales (season, year). High interception variability was observed during rainfall events. The interception ranged between 46% and 72% depending on event duration and intensity (Holko 2010). The relationship between the open area precipitation and throughfall became more regular for larger rainfall events only (Fig. 3.8).

Another important component of water balance in forested catchments is transpiration. Our sap flow measurements showed that daily transpiration correlated best with global radiation and air humidity (Holko et al. 2015b, Photo. 3.1). Transpiration of the same trees was significantly smaller during a dry summer compared to the wet one (Fig. 3.9). Spruce forest transpiration during a dry summer can be similar to total precipitation during the same period. Analogical behaviour was indicated by measurements at different altitudes. While daily transpiration at higher altitude (more precipitation) reached up to 6 mm, it was only up to 2.5 mm near catchment outlet (less precipitation).

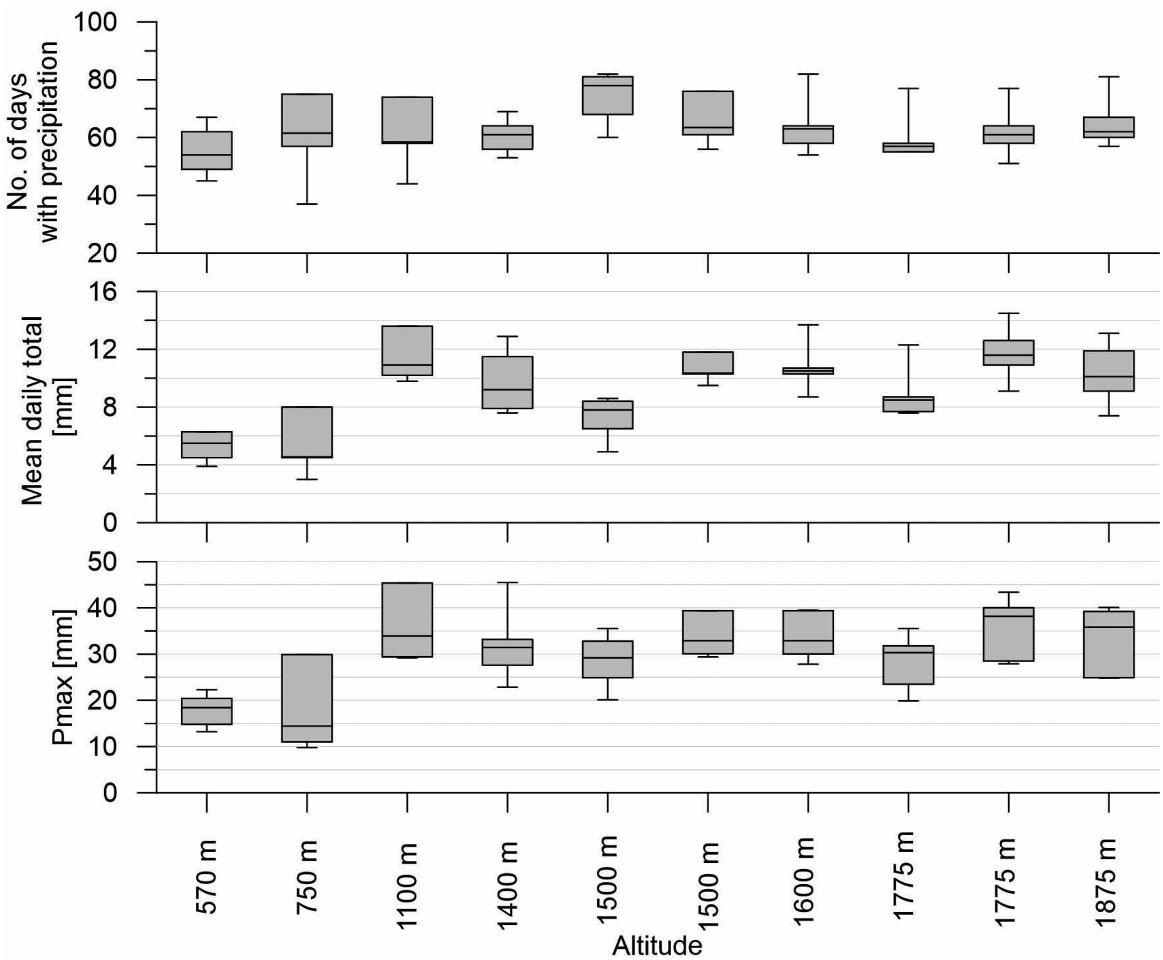

Fig. 3.7. Characteristics of daily precipitation at different altitudes; data from June–September 2013–2017; Pmax is the arithmetic mean of 10 highest daily precipitation totals in each year (Holko, Danko 2018).

Photo. 3.1. Sap flow measurement sites in the Jalovecký Creek catchment (Photo. L. Holko).

Table 3.1. Frequency of daily precipitation totals at different altitudes; altitudes up to 820 m a.s.l. represent the foothill part of the catchment (data June – September 2013–2017).

Daily precipitation	Altitude [m a.s.l.]									
	570	820	1100	1400	1500 leeward	1500 windward	1600	1775 windward	1775 leeward	1875 summit
< 10 mm	83.0	84.1	64.5	66.0	75.3	60.7	61.1	59.8	70.9	65.1
10–20 mm	12.3	9.4	19.9	21.1	15.7	21.5	22.7	22.8	16.9	19.3
20–30 mm	2.2	4.0	8.7	5.3	4.3	9.7	8.4	8.0	7.3	8.0
30–40 mm	2.2	1.8	2.4	4.3	1.6	3.7	2.8	4.2	2.6	3.4
40–50 mm	0.0	0.4	2.8	1.3	1.9	2.3	3.1	2.9	1.3	2.8
> 50 mm	0.4	0.4	1.7	2.0	1.1	2.0	1.9	2.3	1.0	1.5

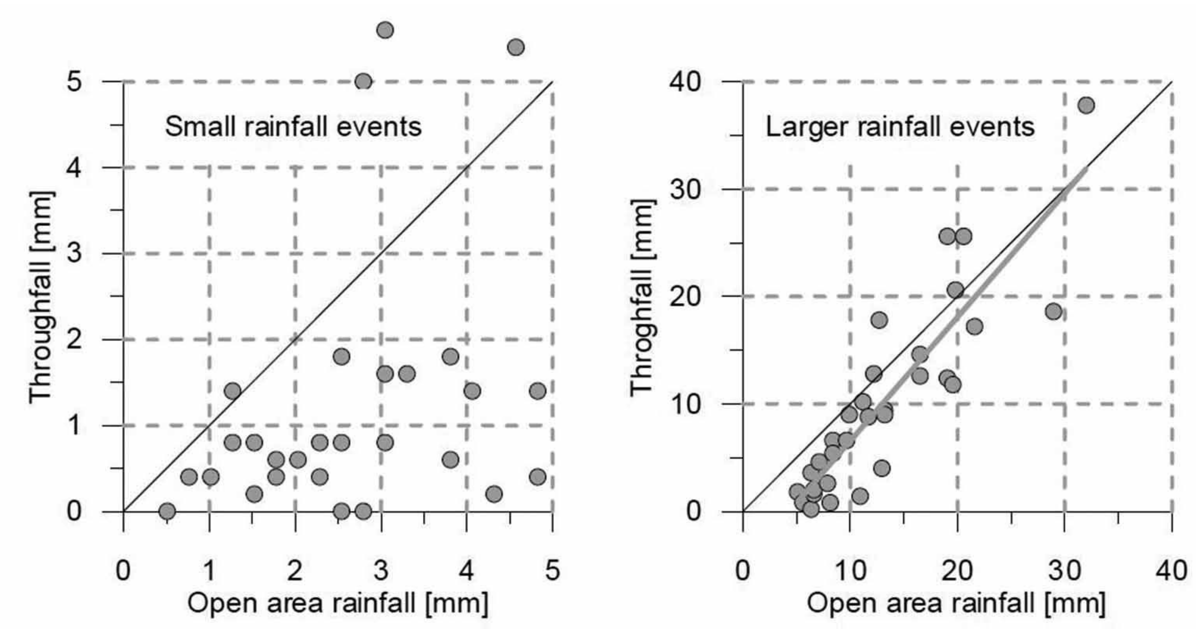

Fig. 3.8. Relationship between the open area rainfall and throughfall for 59 rainfall events measured between 13 May and 13 October 2009; left – total rainfall in the open area from 0 to 5 mm; right – total rainfall in the open area higher than 5 mm; the diagonals represent the 1:1 lines; the grey line in the right panel represents the regression line ($R^2 = 0.778$, Holko 2010).

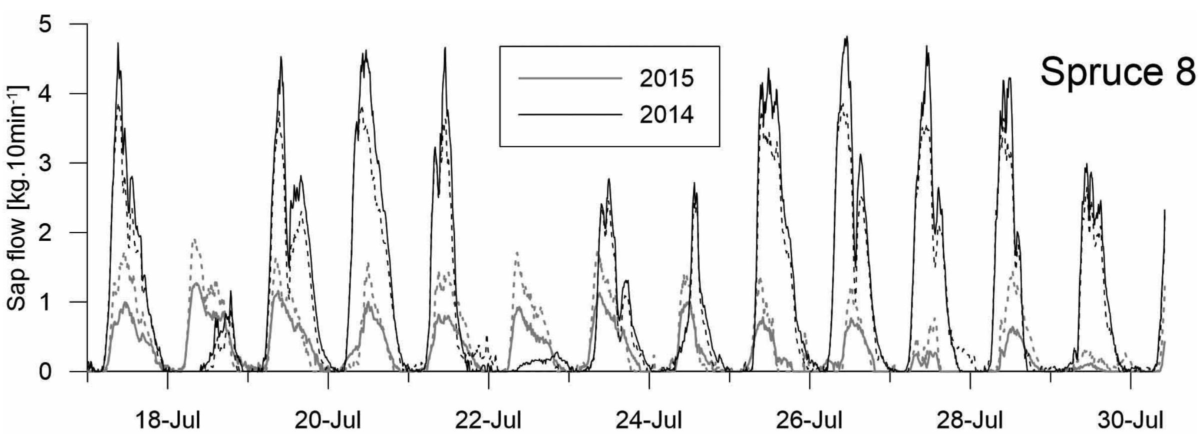

Fig. 3.9. Sap flow measurement plot near the forest line at 1450 m a.s.l. and measured sap flow in the same tree (two sensors in each tree) in the wet summer 2014 (the black line and dashed line) and in the dry summer 2015 (the grey line and dashed line).

Soils form an important hydrological interface between precipitation and runoff. Mountain soils (cambisol, podzol, lithosol, rendzina) contain a lot of skeleton. Maximum stoniness measured in the Jalovecký Creek catchment was 0.6–0.7 cm·cm^{-3} (Hlaváčiková et al. 2015). The stoniness decreases retention of water in the soil layer and increases the percolation. The higher the initial soil moisture, the faster is the outflow from the soil at its lower boundary. High stoniness of mountain soils can be one of the reasons of fast runoff response to precipitation. Soil moisture at greater depth (20 cm) had smaller range and absolute values than near the soil surface (depths 5 cm and 10 cm, Fig. 3.10). Although the seasonal variability of the soil moisture is high, its spatial variability is even higher and reaches several tens of % even at a small area (Fig. 3.11). Nevertheless, Fig. 3.11 shows that despite the variability, the spatial patterns tend to be similar.

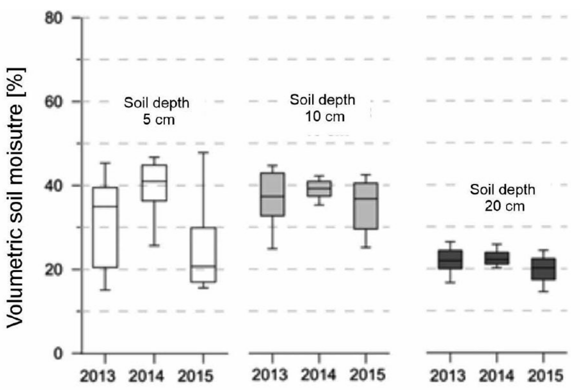

Fig. 3.10. Soil moisture variability in period May – September at different soil depths (1500 m a.s.l.; Hlaváčiková et al. 2018, modified).

Regular decrease of the soil moisture was observed in the foothills in June–July. The duration of the decreased soil moisture period varied in different years. Such a behaviour was not observed at higher altitudes that receive more precipitation (Fig. 3.12). Fig 3.12 documents fast response of catchment runoff to rainfall. The peakflow typically occurs within 1–3 hours after maximum precipitation and flow characteristics (peakflow, total discharge during an event) correlate best with precipitation amount and soil moisture deficit. However, when the rain intensity exceeded certain threshold (0.4 mm·10 min^{-1}) time lag of peakflow after the rainfall became insensitive to the soil moisture deficit (Kostka 2009).

Measurement of soil moisture at several depths allowed estimation of preferential (macropore) flow that occured approximately during one half of rainfall events and always occured at higher rainfall intensities (more than 4 mm·10 min^{-1}). Most of the water moved through the soil in macropores (Hlaváčiková et al. 2018).

Hydrograph separations using stable isotopes of oxygen and hydrogen indicated that catchment runoff was often dominated by the water stored in the catchment before the rainfall or snowmelt, i.e. by the pre-event water (e.g. Holko et al. 2018). The event water contributions to total catchment runoff during the rainfall-induced runoff events were mostly less than 20–30% (the remaining water coming from the catchment storage). Rainfall simulator experiments (Holko et al. 2018) showed that typically only up to 10% of the rain ran off as the overland flow after the intensive rains of short durations (up to about one hour during the repeated rainfall experiments). Maximum snowmelt water contribution to total catchment runoff after the snow-rich winter 2012 reached about 60%. However, the first snowmelt runoff events were almost solely contributed by the pre-event water (Holko et al. 2013).

Catchment runoff in the small catchments of the Tatra Mountains during the rainless snowmelt periods exhibits regular diurnal variability (similar to that known from the glaciated catchments). The beginning and end of such periods and the timing of peakflows in particular years depend on the amount of snow and weather conditions during the snowmelt. Although the snow cover represents a lot of water which is released into the streams in a relatively short period (approximately one month), the snowmelt usually does not result in big floods.

Longer-term variability of climatic and hydrological characteristics and hydrological response to disturbances

A number of studies analysed the long-term climatic (air temperature, precipitation) and hydrological data (runoff, snow depth) measured in the Tatra Mountains and their vicinity. It is good to keep in mind that – similarly to other mountains – most of meteorological stations are located at lower altitudes outside the mountains and that unlike climatic data which are the point values, catchment runoff represents an integrated areal characteristic of the studied area. Calculation of catchment precipitation and air temperature is affected by uncertainties related to the density of point observations (which is never high enough in mountains) and interpolation methods (which are more suitable for calculation of the longer-term climatic characteristics, e.g. annual or seasonal rather than daily or sub-daily). For these reasons there are almost no studies analysing climatic and hydrological conditions of the Tatra Mountains on the catchment scale.

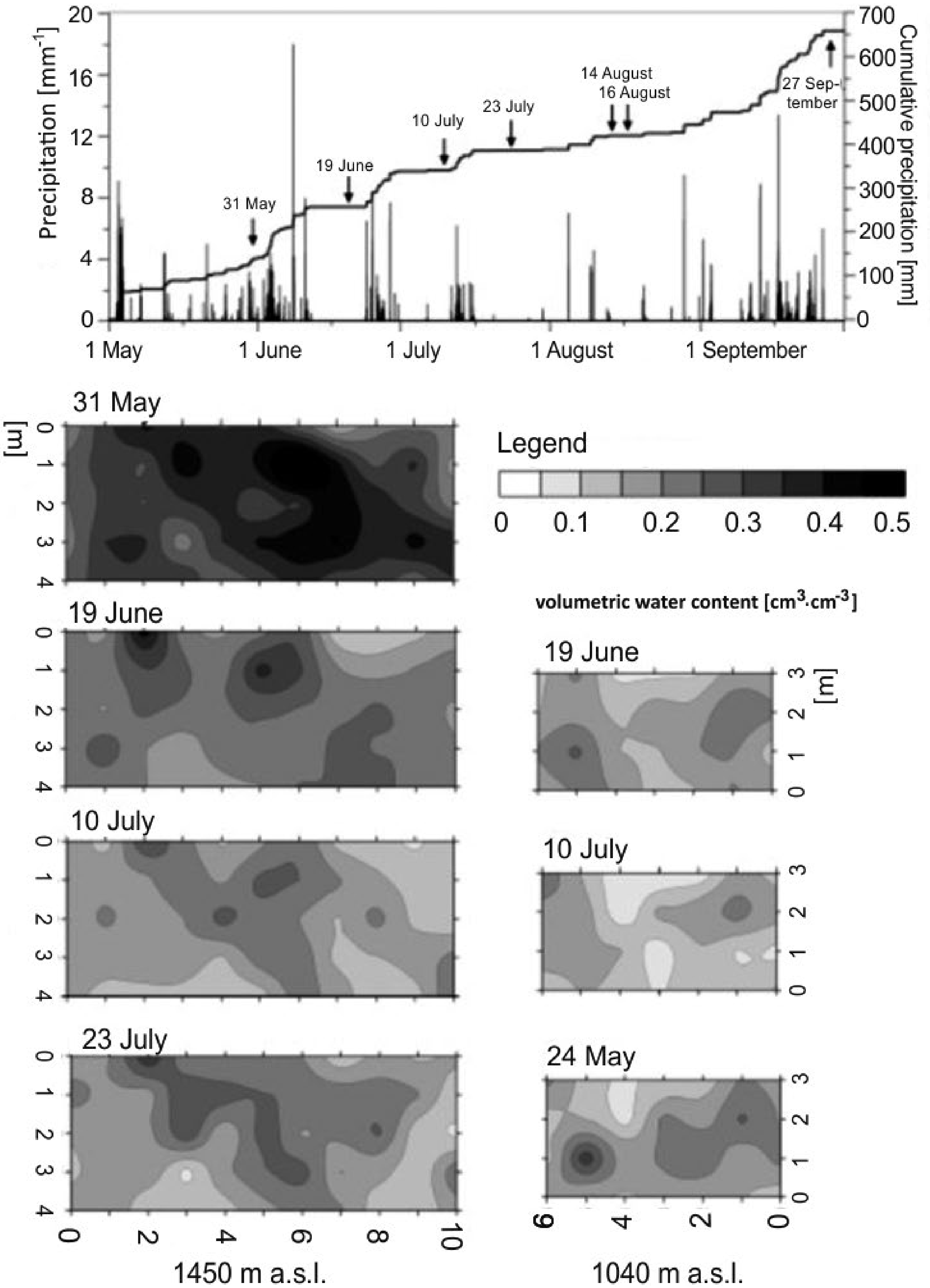

Fig. 3.11. Precipitation and spatial variability of soil moisture at two research plots (at 1450 m a.s.l. and 1040 m a.s.l.) in the spruce forest in vegetation season 2013, the size of the plots is given by numbers at the bottom of the figure (Hlaváčiková et al. 2016, modified).

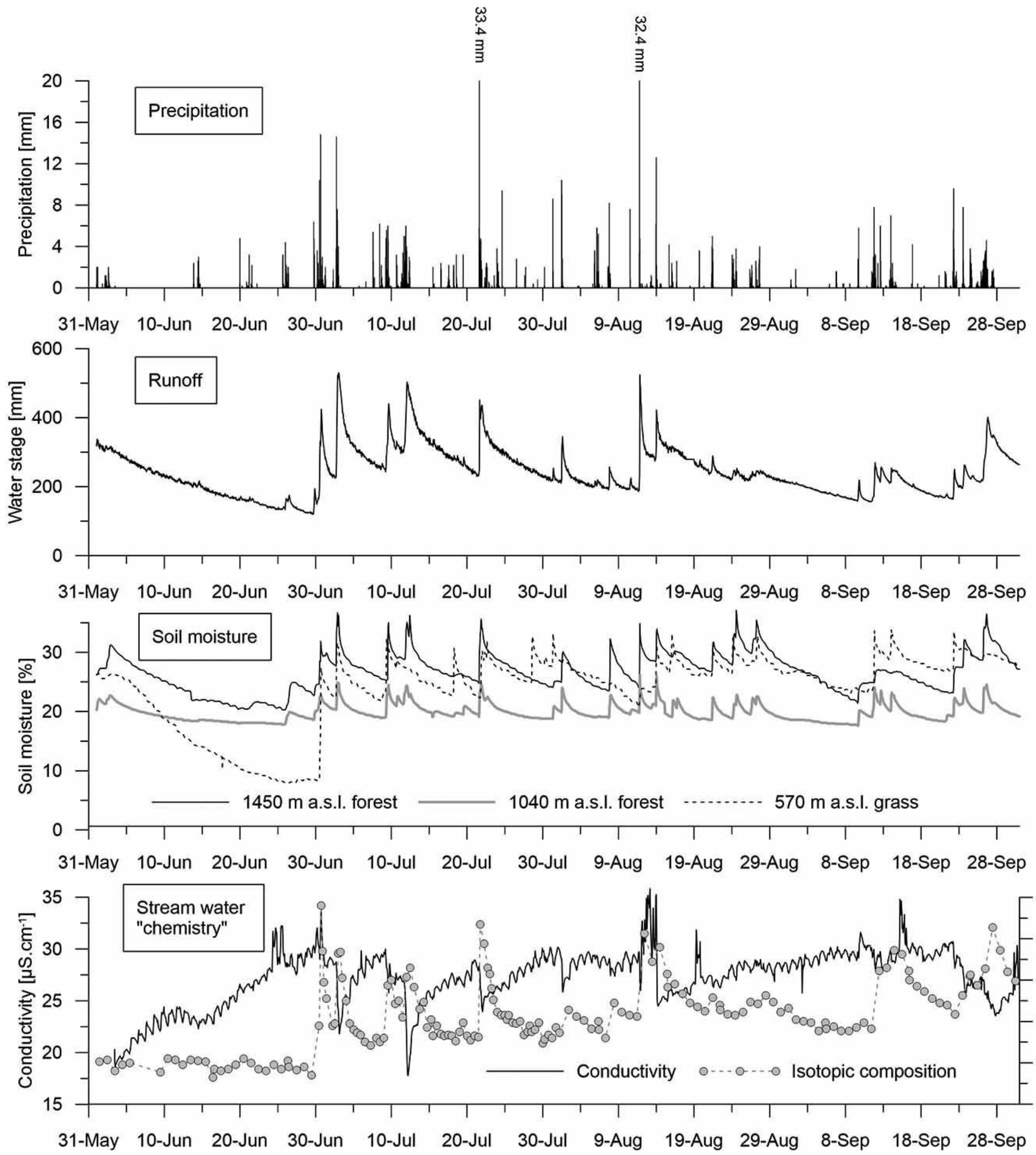

Fig. 3.12. Hourly precipitation (at 1600 m a.s.l.), catchment runoff (represented by the water stage at the outlet of moutains; 820 m a.s.l.), soil moisture in the mountains and foothills and response of stream water conductivity and oxygen isotope ($\delta^{18}O$) in wet summer 2014.

An overview of selected studies analyzing the long-term climatic and hydrological characteristics in the Tatra Mountains is provided e.g. by Bičárová and Holko (2013), Pociask-Karteczka et al. (2010) and Gornik et al. (2017). Numerous studies reported the increase in air temperature in the Tatra Mountains in the second half of the 20th century, e.g. Bokwa et al. (2013), Pribullová et al. (2013), Łupikasza et al. (2016). Mello et al. (2013) reported slight decrease in annual precipitation in period 1881–2009 and the upward shift of climatic belts in the period 1980–2009. However, Halmová and Pekárová (2011) concluded that daily discharges (1928–2008) of the Belá did not show important changes in the number of extreme floods and the temporal extent of droughts. On the other hand, recent research of flood trends in two headwater catchments in the Polish part of the Tatra Mountains revealed positive trends of the annual maximum discharge in the last four decades (Ruiz-Villanueva et al. 2016). Bičárová and Holko (2013) found a significant increase in the number of days with daily precipitation 40–60 mm and increased precipitation at higher elevations in the Slovak High Tatra Mountains in period 1961–2010 and related it to the more frequent occurrence of the long term wet periods in decades 1991–2010. The same result was obtained in the analysis covering the entire High Tatra Mountains territory (i.e. Slovak and Polish parts) by Górnik et al. (2017).

As it was already mentioned, there are just a few meteorological stations in the Tatra Mountains with long records that are located at higher altitudes (Fig. 3.4). They include Štrbské Pleso (1354 m a.s.l.) and Skalnaté Pleso (1778 m a.s.l.) on the southern (leeward side of the Tatra Mountains) and Kasprowy Wierch (1991 m a.s.l.) on the main ridge of the Western Tatra Mountains. Meteorological station Lomnický *štit* (2635 m a.s.l., the first measurements since 1940) is built on the summit of the second highest peak of the Carpathian Mountains. It provides valuable data from the free atmosphere boundary, but precipitation data are affected by its summit position.

The analysis of meteorological data measured at Skalnaté Pleso since the 1940s indicates a significant increase of the annual air temperature and a slight increase of annual precipitation approximately since the year of 2000 (Bičárová 2019). The snow cover depth data show two main periods – higher snow depth approximately until the mid-1960s and lower snow depth since the beginning of the 1970s (Fig. 3.13).

Fourier analysis of the snow depth data of the second period (1971–2012) revealed the cycle with period of approximately 8 years (Holko 2012). Wavelet analysis of precipitation, air temperature and runoff in the Jalovecký Creek catchment for period 1988–2017 indicated cycles with periods 3–4 years, 6–8 years and 3–4 years, respectively (Sleziak, unpublished data). Similar periodicity (3.6 years) was found by spectral analysis of the annual runoff data of the Belá river (1895–2002) by Pekárová and Pekár (2007). Except the main cycle of 3.6 years Pekárová and Pekár (2007) also identified cycles 29 years, 36 years, 13 years, 4.2 years and 2.4 years long.

Hydrological cycle in the Tatra Mountains is not affected only by the climatic variability, but also by other disturbances, among them windthrows and related bark beetle outbreaks. Strong falling winds frequently damage the forest on the southern (leeward) side of the Tatra mountains, but the windthrows occur also on the northern (windward side). The most severe wind disturbance hit the Tatra Mountains (mainly the High Tatra Mountains) in November 2004. The wind gust exceeded 230 km·h^{-1} and laid down some 30% of the forest on the southern side of the mountains. The forest was destroyed (mostly broken) in a belt which was about 2–5 km wide and 40–50 km long (area about 120 km^2). High summer temperatures in the following years caused forest fires and unprecedented European spruce bark beetle (*Ips typographus*) outbreaks (Flesicher et al. 2017). Fleischer et al. (2017) concluded that even 10 years after the disturbance, all ecosystem services, i.e. the provisioning, regulating and cultural services were still below the pre-disturbance state. Interestingly, analyses of hydrological characteristics from the small catchments of the High Tatra Mountains (catchment areas 17–315 km^2) conducted several years after the disturbance could not prove any serious changes that would have been clearly attributed to the windthrow (Holko et al. 2009). Water balance, minimum and maximum runoff, quantiles, number of runoff events, selected characteristics of events, runoff coefficients, and flashiness indices were analysed first, followed by the analysis of baseflow, comparison of runoff response to significant rainfall events and finally the flow duration curves (Holko, Škoda 2016).

Some characteristics that might indicate the influence of the windrow are shown in Figs 3.14 and 3.15. However the analyses showed that "we do not have suitable indicators of catchment runoff changes for the mountain catchments with area of several tens of square kilometers in which the forest reduction reached 20–32%" (Holko, Škoda 2016).

Unclear evidence on the impacts of the extraordinary deforestation in the High Tatra Mountains on the hydrological cycle at the catchment scale was probably caused by several factors (Holko et al. 2009):
- most of the deforestation, while quite extensive, occurred in the middle sections of the catchments; the headwaters, where most of the runoff forms and where little forest exists anyway, were not impacted;
- deforestation occurred in areas formed by moraines that are assumed to have a high infiltration capacity;
- deforestation affected relatively small percentages of catchment areas since it went across the catchments in the east-west direction while the catchments are generally north-south oriented; thus, not all the forests were destroyed.

Fast regrowth of plants and other vegetation probably also contributed to the fact that the serious floods were not recorded after the disturbance.

Almost 15 years after the windthrow it has to be stressed that the land cover of the southern part of the Tatra Mountains has been changing rapidly in the last years. Forest dieback continues and a number of newly deforested areas appear. While the dieback is related to natural processes, this development should be observed with caution.

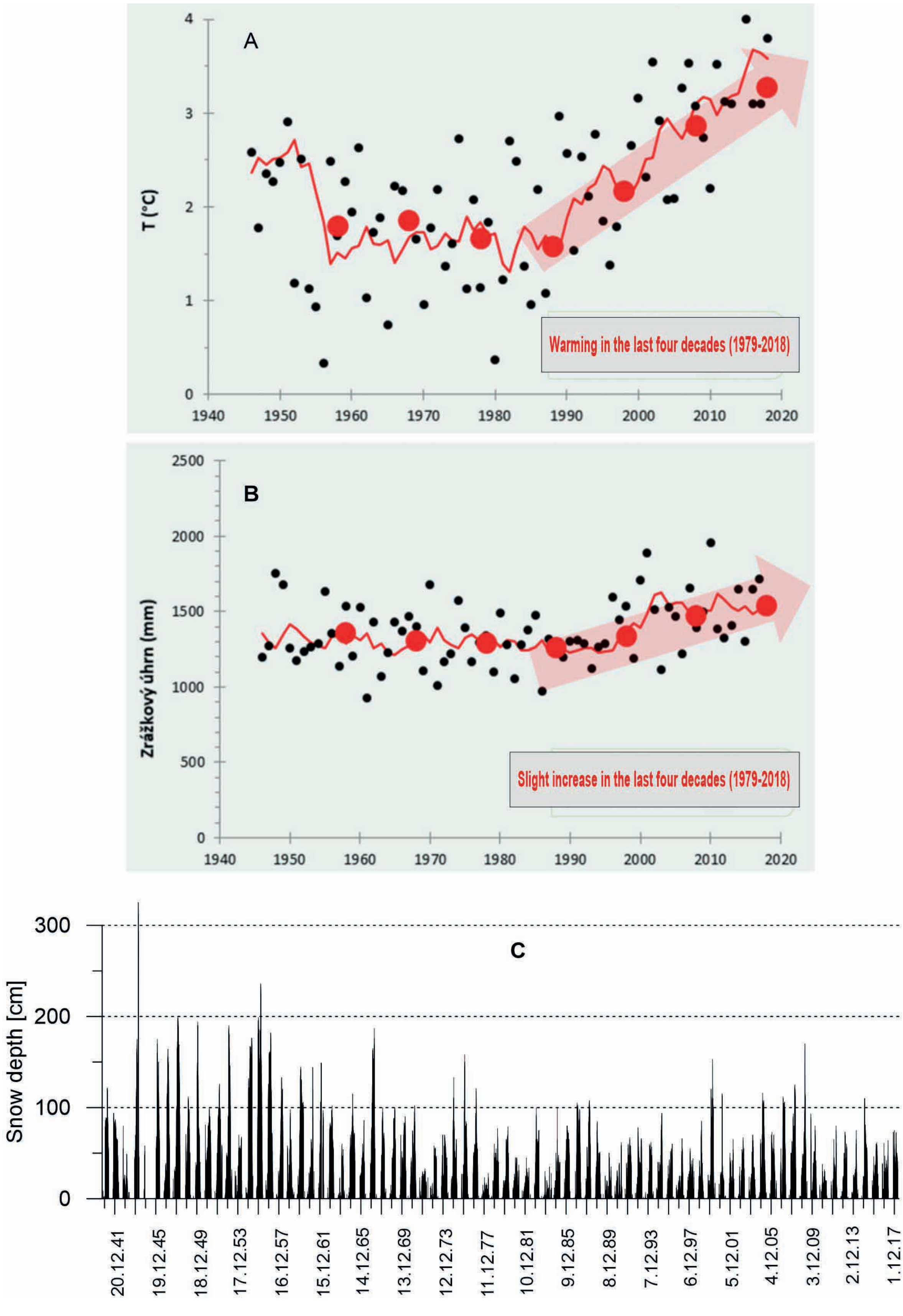

Fig. 3.13. Annual air temperature (A), precipitation (B) and daily snow depth (C) at Skalnaté Pleso since the 1940s until 2018; the small dots in A and B show annual values, the lines are the Holt-Winters smoothed values and the big circles represent the decadal averages (Bičárová 2019, modified).

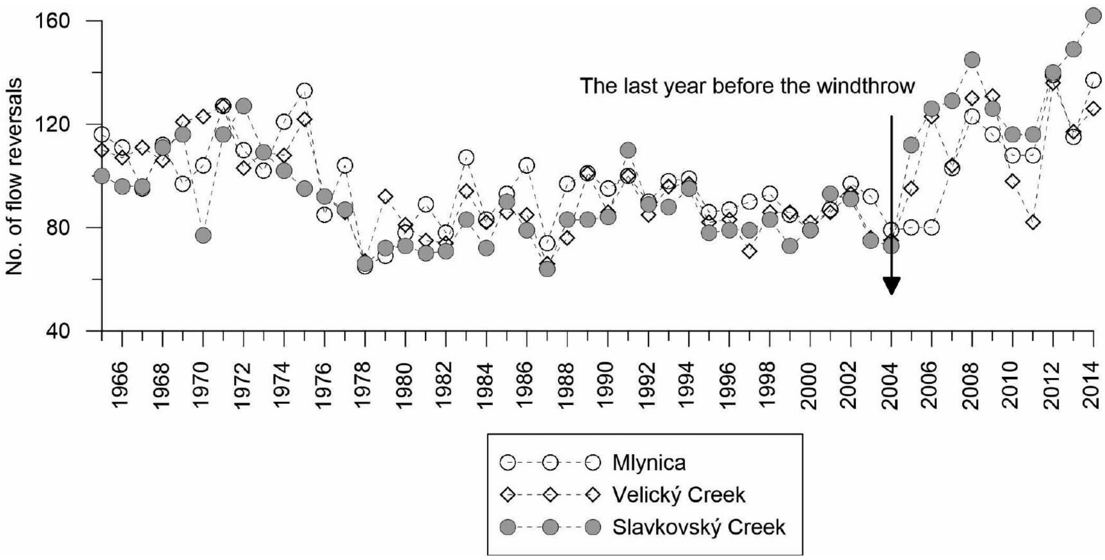

Fig. 3.14. Frequency of flow reversals (changes from the increasing to decreasing flow and vice versa) in hydrological years 1965–2014 in three catchments in the High Tatra area; the Mlynica catchment was almost unaffected by the deforestation (5% decrease of forestation), forest cover in the Velický Creek and Slavkovský Creek catchments decreased by 20% and 32%, respectively (Holko, Škoda 2016; modified).

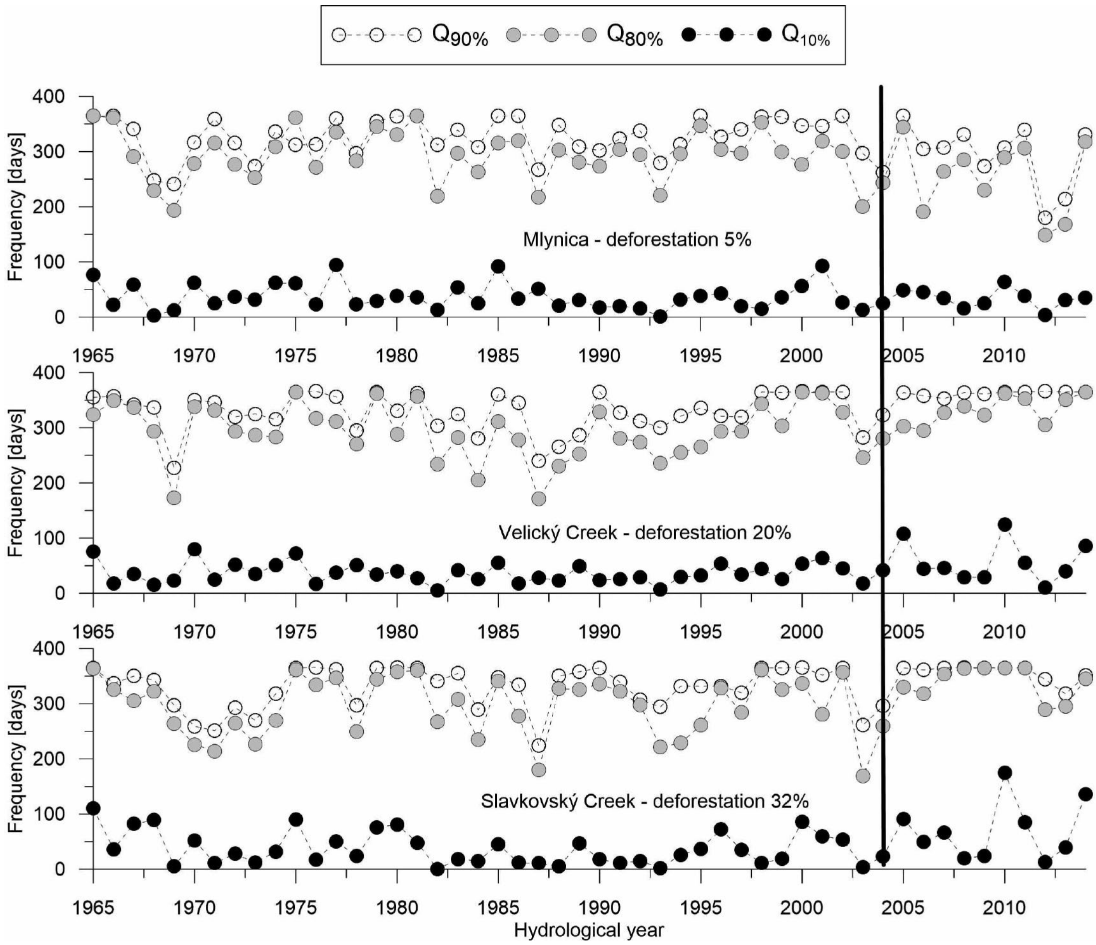

Fig. 3.15. Frequencies of the occurrence of quantiles $Q_{90\%}$, $Q_{80\%}$ and $Q_{10\%}$ of daily flows calculated from the median flow duration curve for period 1965–2004; the vertical line shows the last year before the windthrow (Holko, Škoda 2016; modified).

Conclusions

The Tatra Mountains have an important influence on the downstream areas. Precipiation water captured at high altitudes flows via the stream network or groundwater aquifers to other regions (the lowlands and uplands) where the demand from population centres, agriculture and industry is high. Hence, the Tatra Mountains are the "water tower" for Central Europe, a place of a storage and distribution of water to regions both in the Baltic Sea and the Black Sea basins (Photo. 3.2).

Photo. 3.2. High mountain part of the Slovak Tatra Mountains (Skalnaté Pleso station, Photo. L. Holko).

Molnár and Pacl (1988) calculated that although the Slovak Tatra Mountains cover only 3% of the area of Slovakia, their contribution to runoff from Slovakia is 9%. Infiltration of precipitation at high elevations of the Tatra Mountains and its deep percolation through joints and faults give birth to thermal water and important drinking water resources.

Utilization of the surface water resources in the Tatra Mountains is limited by minimum discharges of the streams that occur in winter months. Much of the potential of surface water resources is already exhausted and greater natwural resources can be obtained only in certain sections of the Poprad river which is the main river draining the southern part of the High Tatra Mountains (Malík et al. 2005), and the Dunajec and Białka draining the northern part of the Polish Tatra Mountains (Kot 2019). Drinking water supply is provided mainly from springs recharged by Mesozoic rocks, Quarternary fluvial, glacial and glaciofluvial aquifers. The groundwater potential is still high since only about 9% of groundwater resources were utilized at the beginning of this millenium (Malík et al. 2005).

Hydrological knowledge obtained from regular and research networks in the Tatra Mountains that was partially presented above, can be used not only in better understanding and management of water resources and hazards, but also in protection of nature in this beautiful region.

Chapter 4

Environmental and anthropogenic factors affecting water chemistry in the Polish Tatra Mountains

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Abstract: The aim of the chapter is to analyze the environmental and anthropogenic factors affecting groundwater, stream water and lake water chemistry in the Polish Tatra Mountains. Geology is the most important environmental factor determining water chemistry in the Polish Tatra Mountains. In the crystalline portion of the Tatra Mountains formed of poorly soluble granite and gneiss rocks, the total dissolved solids and concentration of main cations and anions are many times lower than that in the sedimentary portion of the Tatra Mountains formed of highly soluble carbonate rocks. Hydrologic factor (changes in discharge) drives stream water and spring water chemistry changes in the course of the year and during rainfall and snowmelt events. Soil cover properties such as their thickness and chemistry are additional environmental factors affecting water chemistry in the Tatra Mountains. Anthropogenic factors influencing water chemistry in the Tatra Mountains include acid rain, deforestation, and tourist traffic.

Key words: groundwater, streams, lakes, geology, lithology, human impact

INTRODUCTION

The chemistry of both surface water and groundwater is affected by many different environmental and anthropogenic factors. The most important environmental factors are usually lithology, soil cover, vegetation, and hydrology, while the most important anthropogenic factors are wastewater discharge and fertilizer use (Hem 1985). The Tatra Mountains are located within the borders of a large national park in Poland and Slovakia and are an area experiencing relatively little human pressure. Therefore, this region provides favorable conditions for the identification of natural factors controlling water chemistry. However, water in this region remains under the strong impact of tourist traffic and the impact of long-distance air pollutants (Rzychoń, Worsztynowicz 2008). The identification of factors controlling water chemistry in high mountains in the broadly defined Baltic Sea region, for example in the Tatra Mountains, is an important issue because of the crucial role of mountains in the water chemistry of rivers flowing further downstream.

Geology

Groundwater, stream water and lake water chemistry varies across the Polish Tatra Mountains (Fig. 2.5). This is the result of large geologic variation in the region. The southern part of the Tatra Mountains is made of poorly soluble crystalline rocks: metamorphic rocks (mainly gneiss and crystalline shale) and alaskite in the Western Tatra Mountains, and granitoids (granodiorites) in the High Tatra Mountains. The northern part of the Tatra Mountains is formed of well-soluble sedimentary rocks: dolomitic limestone, limestone, dolomite, sandstone, shale, and conglomerates (Passendorfer 1996). Total dissolved solids (TDS) and the concentration of main ions in groundwater, stream water and lake water are very low in the crystalline part of the Tatra Mountains (Małecka 1989; Oleksynowa; Komornicki 1996; Żelazny 2012; Sajdak et al. 2018a). For example, the mean TDS of spring water (n = 489) across this part of the Tatra Mountains is only 33.7 mg·dm^{-3} (Żelazny 2012). TDS and the concentration of main ions in the crystalline Western Tatra Mountains are about twice as high as in the crystalline High Tatra Mountains (Photo 4.1). This is due to the slightly better solubility of crystalline rocks in the Western Tatra Mountains than in the High Tatra Mountains. In the northern sedimentary part of the Polish Tatra Mountains, TDS and the concentrations of main ions of groundwater and stream water are distinctly higher than in the southern crystalline part of the Tatra Mountains. For example, according to Żelazny (2012), the mean TDS of spring water in this part of the Tatra Mountains is 245.1 mg·dm^{-3} (Fig. 4.1). According to Małecka (1989) and Małecka et al. (2007), the chemistry of precipitation affects ap. 90% of groundwater and stream water chemistry at high elevations in the southern parts of the Tatra Mountains where the solubility of crystalline rocks is very low. The effect of precipitation on water chemistry did not exceed 30% at lower elevations in the sedimentary part of the Tatra Mountains.

Photo. 4.1. Field measurements of physical properties of water in the Tatra Mountains (Photo. J. Pociask-Karteczka).

Spatial diversity of water chemistry in the Tatra Mountains are determined by local geology and have been used thus far as the basis for the hydrochemical regionalization of the Polish Tatra Mountains. The first regionalization was performed by Oleksynowa (1970) who identified three hydrochemical regions: (1) crystalline Tatra Mountains area, (2) transitional region of crystalline and sedimentary rocks, (3) sedimentary Tatra Mountains area. Another regionalization was done by Małecka (1989) who identified three hydrochemical regions characterized by a belt-type pattern related to the tectonic and geologic structure in the Polish Tatra Mountains. The first region includes areas formed of both crystalline rocks and quartzite sandstone. The second region includes areas formed of the High-Tatric Units sedimentary rocks – mainly limestone. The third region includes areas formed of the Sub-Tatric Units sedimentary rocks – mostly conglomerates, dolomitic limestone, as well as nummulites of the Eocene. There is a newest hydrochemical regionalization developed by Żelazny (2012), who used multidimensional analysis of variances in spring water chemistry. He recognized two main hydrogeochemical environments associated with (Fig. 4.2):

1. sedimentary rocks,
2. crystalline rocks.

For the studied sedimentary rock environment, he identified three distinct sub-types: (1) dolomite-limestone, (2) dolomite-limestone-sulfate, (3) limestone. For the crystalline rock environment, he distinguished two sub-types: (1) granitoid environment, (2) metamorphic environment (Fig. 4.2). Spring water in the Tatra Mountains may be placed in 15 hydrochemical categories. The most common water categories are HCO_3^-–Ca^{2+}–Mg^{2+} (45.4%) and HCO_3^-–Ca^{2+} (24.3%). The degree of hydrochemical variation is greater in the crystalline core (13 types) versus the sedimentary core (9 types). The most common components of the crystalline core are SO_4^{2-} (53.2%), quite frequently Mg^{2+} (41.3%), and less frequently Na^+ (14.1%). On the other hand, the most common component of the sedimentary rocks is Mg^{2+} (74.7%), and to a much lesser extent, SO_4^{2-} (8.1%). Spring hydro-geochemical types follow a mosaic-type spatial pattern that is linked closely to lithologic determinants (Żelazny 2012).

Soils

Soil properties such as their thickness, texture and chemistry usually control the ion influx to lakes and streams (e.g. Mulder et al. 1995; Seibert et al. 2009; McDowell, Liptzin 2014). According to Sajdak et al. (2018b), the high concentration of Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^- and NO_3^- in the stream water in crystalline part

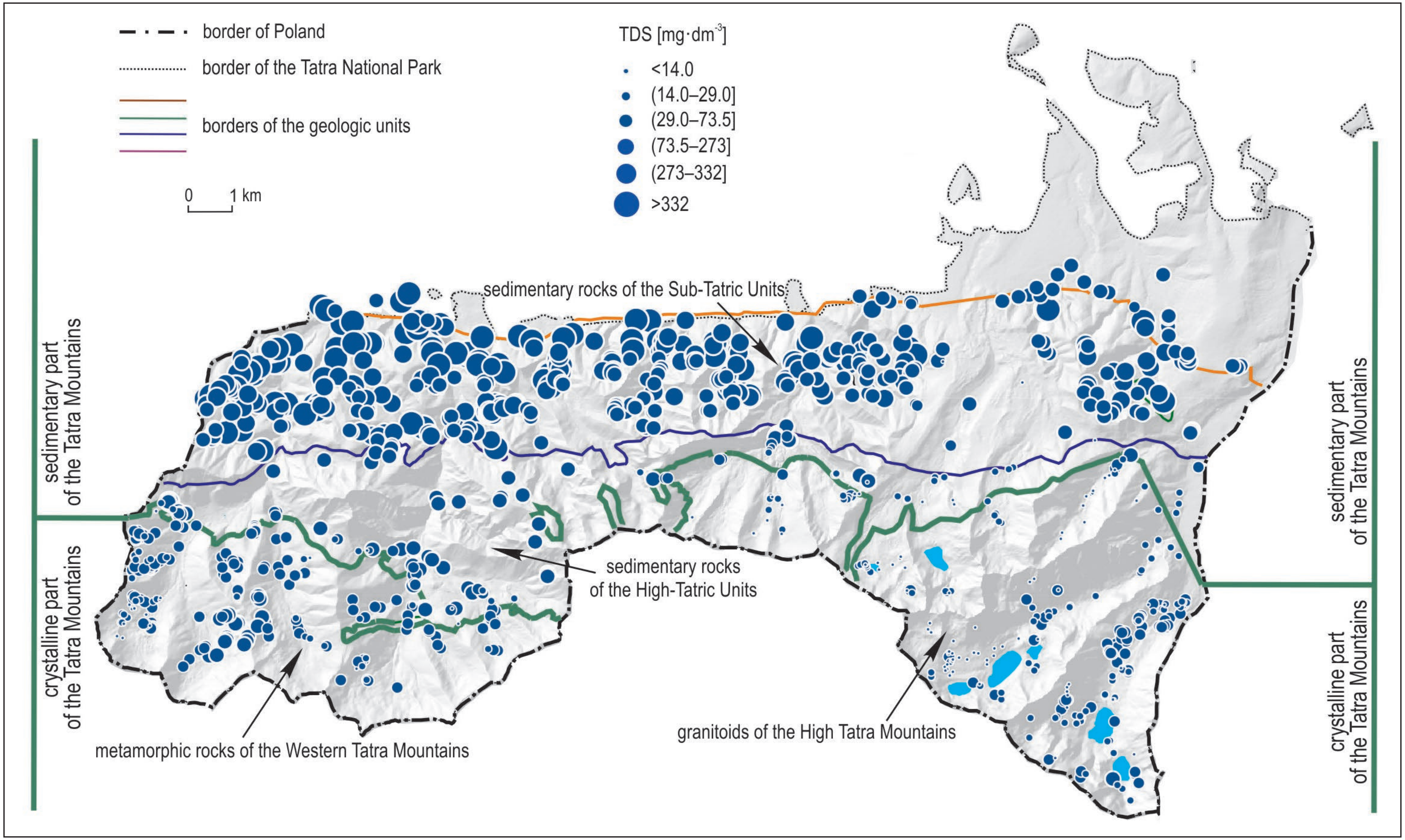

Fig. 4.1. Total dissolved solids (TDS) of spring water in the Polish Tatra Mountains (Żelazny 2012, modified).

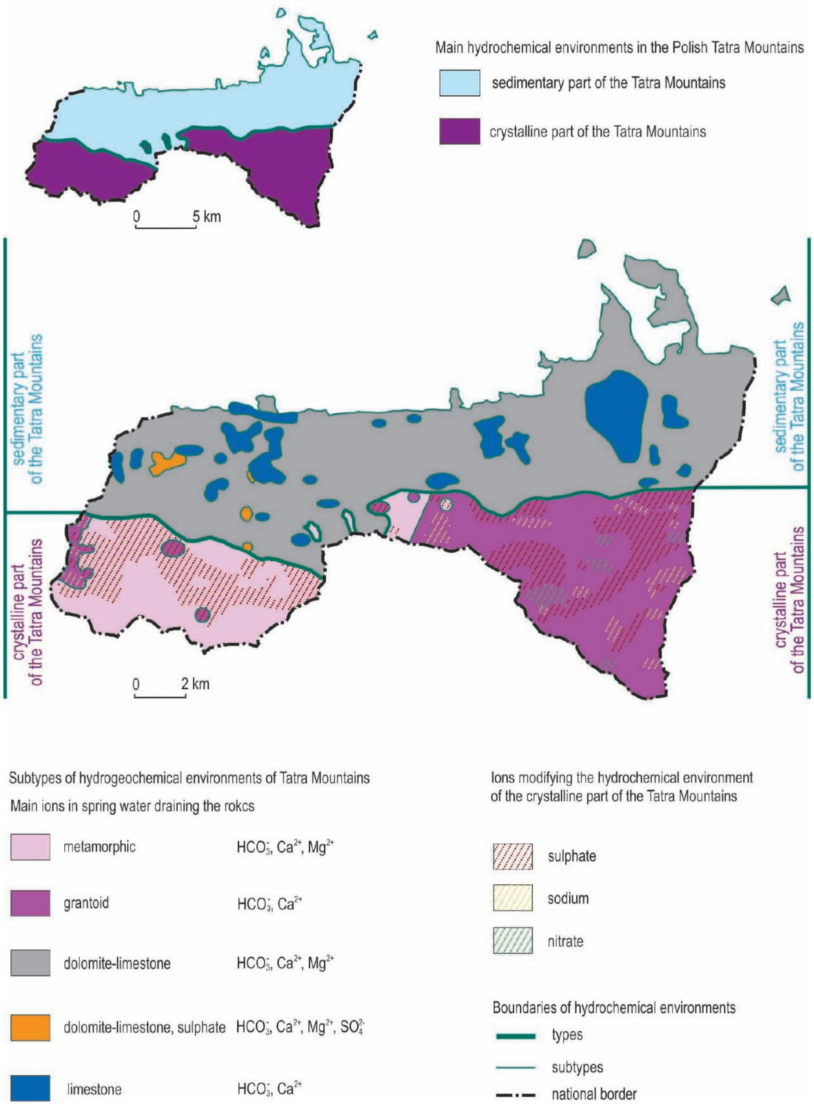

Fig. 4.2. Hydro-geochemical environments in the Polish Tatra Mountains (Żelazny 2012, 2015c, modified).

of the Tatra Mountains at the beginning of rain-on-snow events results from ion leaching from shallow soils: Regosols, Entic Podzols, Leptic Podzols, Folic Leptosols, and Haplic Podzols. However, Kopáček et al. (2004a) found no significant correlation between soil chemistry and the concentration of some main ions and nutrients in Tatra lakes. They found a correlation between organic matter concentration in soils and nutrient (C, N, and P) concentrations in lakes. The amount of soil and soil exchangeable base cation capacity determines the sensitivity of Tatra lakes to acidification (Kopáček et al. 2004b; Stuchlík et al. 2006). Lakes draining catchments with a large amount of soil and high soil exchangeable base cation capacity are more resistant to acidification than lakes draining catchments with a small amount of soil and low soil exchangeable base cation capacity. A small amount of soil results in a low ability of catchments to retain acidic nitrogen derived from atmospheric deposition, thus leading to a high concentration of NO_3^- in lake water. Low soil exchangeable base cation capacity results in a low acid neutralizing capacity of lakes and low pH of lake water (Kopáček et al. 2004b).

Hydrology

Changes in discharge over the course of the year are the most important factor controlling the seasonal variation of stream water and spring water chemistry in the Tatra Mountains. The influx of snowmelt water in the spring and rainwater in the summer is characterized by low TDS and a low concentration of most main ions, which results in a decrease of these parameters in stream water and spring water with increasing discharge. The rate of seasonal change in spring water chemistry depends on the amount of rainfall as well as the thickness, density, and melting rate of snow cover (Wolanin, Żelazny 2010; Wójcik 2012; Żelazny 2012; Wolanin 2014; Sajdak et al. 2018a). There are two types of stream hydrochemical regimes in the Tatra Mountains:

– high mountain regime,
– middle mountain regime.

For both regimes, the lowest TDS and concentration of most main ions occur during the spring snowmelt season. However, in streams characterized by a high mountain regime, the lowest TDS, lowest conductivity, and lowest ion concentrations occur later than in streams characterized by a middle mountain regime. This is due to the snowmelt season occurring later and lasting longer at higher elevations than at lower elevations (Żelazny 2012).

The most dynamic changes in stream water chemistry in the Tatra Mountains occurred during rainfall and snowmelt events. Streams are supplied by groundwater alike throughflow and overland flow. Throughflow and overland flow water are characterized by a distinctly lower concentration of most main ions than groundwater due to less contact time with parent material. Hence, dilution is the main factor controlling stream water chemistry during events in the Tatra Mountains (Sajdak et al. 2018b). Changes in some ion concentrations triggered mainly by dilution sometimes are also affected by other processes. For example, an unexpectedly large increase in HCO_3^- at the beginning of a rain-on-snow event in the mountain creek may be triggered by a rapid influx of pre-event ("old") water from the local karst system (Sajdak et al. 2018b).

Acid rain

There is a decline in the concentration of main cations in some lakes in the High Tatra Mountains (Zielony Staw lake and Długi Staw lake) due to the long-term acidification of precipitation in the area. The pH of bulk precipitation ranged from 4.39 to 5.16 and an increasing trend in the pH of atmospheric precipitation occurred in the Tatra Mountains in the years 1992–2005 (Rzychoń, Worsztynowicz 2008). Acid rain pollution originates mostly in locations far away from the mountain range. There are seasonal fluctuations in precipitation acidity: lower pH was noted during the winter than during the summer. This was explained by unique meteorologic conditions in winter causing an inflow of industrial pollution from faraway locations and higher local sulfur deposition in the heating season (Grodzińska-Jurczak 1995). The lowest pH of snow occurs near cities such as Zakopane and Kościelisko, and near tourist lodges (Żelazny, Kasina 2009).

Deforestation by windfalls and bark beetle outbreaks

Forests in the Tatra Mountains are artificially dominated by spruce monocultures (Grodzki, Guzik 2009). Spruce monocultures occupy nearly 80% of the lower montane zone while natural mixed beech-fir forest occupy less than 10% of the zone (Mirek 1996). The spruce monocultures are characterized by low resistance to summer drought, heavy winds, bark beetle infestation, and fungus expansion (Małek et al. 2012, 2014). Hillslope deforestation triggered by hurricane-force winds in 2013 (Photo 4.2) and tree stand decline due to bark beetle infestation has led to significant changes in the water chemistry of springs and streams in the mountain stream catchment in the West Tatra Mountains (Żelazny et al. 2017a, b). Research conducted one and a half years

Photo. 4.2. The Western Tatra after windfall in December 2013 (Photo M. Żelazny).

after deforestation revealed that the mean concentration of NO_3^- in water in areas deforested by winds was 15.44 mg·dm^{-3}, in areas deforested by bark beetle infestation – 6.17 mg·dm^{-3} while in forested areas – only 3.26 mg·dm^{-3}. Hence, the increase of NO_3^- concentration in stream water and spring water caused by deforestation was more than fivefold (Żelazny et al. 2017a). The mean water concentration of NO_3^- on deforested hillslopes continued to increase over time. In the period 2015–2016 the mean concentration of NO_3^- in stream water and spring water in areas deforested by winds equaled 16.53 mg·dm^{-3}, in areas deforested by bark beetle infestation 6.69 while in forested areas 3.06 mg·dm^{-3} (Żelazny et al. 2017b). Such a large increase in the concentration of NO_3^- in deforested areas results in a change in the position of NO_3^- in the sequence of anions from the natural sequence occurring in forested carbonate-type catchments ($HCO_3^- > SO_4^{2-} > NO_3^- > Cl^-$) to the now predominant sequence $HCO_3^- > SO_4^{2-} > NO_3^- > Cl^-$ (Żelazny et al. 2017a, b).

Tourism

The number of visitors in Tatra National Park has remained at about 2.5 million per year for the last two decades (Siwek, Biernacki 2016). The impact of tourist traffic on the natural environment in the Tatra Mountains is distinctly larger than that in other mountain national parks in Europe. For instance tourist traffic in Berchtes gaden National Park in the German Alps equals 57,000 tourists per hectare per year, in Swiss National Park and Hohe Tauern National Park in the Austrian Alps – 9000, while in Tatra National Park – 120,000 tourists per hectare per year (Kurek 2007). Borowiak et al. (2006) found that the water chemistry of some Tatra Mountains lakes located close to mountain lodges is strongly affected by tourist traffic. The shores of these lakes are used as a stopover for many people. Tourist lodges are a major threat to stream water quality *via* their frequent release of wastewater into local streams (Siwek, Biernacki 2015, 2016). Wastewater produced by the mountain lodges in the years 2008–2009 caused significant changes in the concentrations of some nutrients found in streams into which the wastewater was released: the concentration of NH_4^+ in stream water downstream of the wastewater release site was roughly 200 times greater than the concentration upstream of that site, while PO_4^{3-} concentrations were 30 times greater. The NO_3^- content increased substantially also. The largest loads of nutrients were released into streams in the summer season when the discharge of streams is very low. This causes serious ecological threat to stream water quality due to weak wastewater dilution. Wastewater releases from tourist lodges into streams and stream water pollution have been a leading problem in the Tatra National Park for many years. The wastewater management situation in the Tatra National Park has improved markedly since 2009. In 2010 and 2011 wastewater treatment plants at the Murowaniec Lodge and Polana Chochołowska Lodge were fully modernized (Fig. 5.2). In 2011 a new treatment plant was opened at the lodge in the Valley of Five Polish Lakes (Siwek, Biernacki 2015).

Conclusions

The chemical composition of water in the Tatra Mountains has been controlling both by environmental and anthropogenic factors. Complex geology has a crucial significance. For example, the total dissolved solids of spring water in the crystalline part of the Tatra Mountains formed of poorly soluble granite and gneiss rocks is many times smaller than that in the sedimentary portion of the Tatra Mountains formed of highly soluble limestones and dolomites. Other factors, apart from geology, affect water chemistry in the Tatra Mountains to some extent (Fig. 4.3).

Hydrologic factor – changes in discharge – is responsible for seasonal stream water and spring water chemistry changes as well as changes during rainfall and snowmelt events. The influx of meltwater and rain water results in a decrease of TDS and concentration of most main ions in stream water and spring water according to increasing discharge. Soils are an additional environmental factor influencing water chemistry in the Tatra Mountains. Some ions are flushed out of the soil at the beginning of rainfall and snowmelt events. The amount of soil and soil exchangeable base cation capacity determines the sensitivity of lakes to acidification. The Tatra Mountains have been affected by acidic pollution of long-distance transport. The impact of acid rain on water chemistry in the Tatra Mountains results in a decline of main cations concentration. The decline of spruce monocultures in the Tatra Mountains results mostly in substantial increasing of NO_3^- concentrations – even one and a half years after deforestation. Wastewater released from tourist lodges affects stream water chemistry leading to excessive nitrogen and phosphorus concentration. The quality of water in the Tatra Mountains has improved since 2009 owing to modernization wastewater treatment plants in mountain lodges.

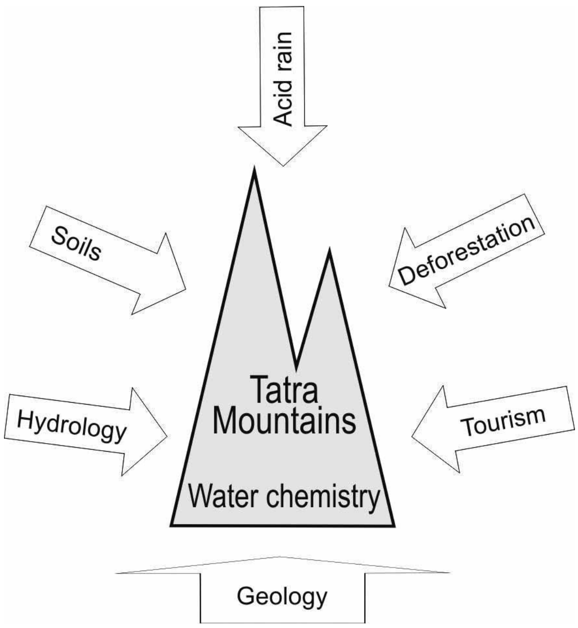

Fig. 4.3. Factors controlling water chemistry in the Tatra Mountains.

Chapter 5

Spatial and temporal variability of water resources in the Polish Tatra Mountains

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Abstract: Increasing human impact on the Tatra Mountains water resources exerted by local residents, tourists, and ski lobby prompted the Tatra National Park to install a modern monitoring network launched in 2008 (42 digital water gauges). The Tatra Mountains streams are characterized by a simple hydrologic regime with one flood season lasting from April to July. Up to 75% of the annual river runoff outflows from the Tatra Mountains catchments in the summer half-year season (May–October). The contribution of base flow is between 30% and 55% and it tends to be the highest in catchments with a relatively high carbonate rock content as well as in catchments with substantial thickness of fluvioglacial cover and moraine cover. The highest spring discharge is attributed to vaucluse springs (Chochołowskie, Goryczkowe, Lodowe Źródło, Olczyskie, Bystrej) which have recharge area beyond the topographic catchments. Two hydrographic regions have been identified in the Tatra National Park dependent on geology complex, which determines water circulation patterns as well as groundwater and surface water: the Tatra Mountains region (I) and flysch region (II). The Tatra Mountains region consists of three subregions: crystalline subregion (Ia), high mountain, karst, limestone, dolomite subregion (Ib), and dolomite, shale, middle mountain subregion (Ic).

Keywords: vaucluse springs, runoff, streams, hydrological regions

Hydrological network

The first water level gauges in streams in the Polish Tatra Mountains were operating in the 1960s (Białka, Cicha Woda) and 1970s (Poroniec, Potok Kościeliski, Czarny Dunajec). These gauges were installed by the national service i.e. the Institute of Meteorology and Water Resources. Subsequently, the scientific group led by Prof. Danuta Małecka from the University of Warsaw (Małecka 1984) has operated a network of gauges supervised by the Tatra National Park (TNP) to 1999. TNP staff have been monitoring water levels at 29 gauges ever since. The number of water level measurements varies seasonally from 4 to 15 per month. Human impact exerted by local residents and tourists on the Tatra Mountains water resources prompted TNP to install a modern monitoring network for both groundwater and surface water as part of its standard water monitoring work. This new network launched in 2008 includes 42 digital water gauges that measure water levels and temperatures at least once per hour (Fig. 5.1). An additional 11 monitoring sites were activated in 2013 that gauge physical and chemical characteristics of water in two river catchments: Bystra and Sucha Woda (Żelazny et al. 2013–2016). The results are viewable online. Furthermore, hydrologic monitoring is performed in the Kościeliski Potok catchment, which is affected by deforestation caused by very strong, gusty winds and the bark beetle. This program has been in effect since 2014 and focused on the effect of deforestation on catchment water resources. In addition to providing research material, these types of monitoring efforts help assess development projects in and around TNP, as well as assist in determining limits of water resources exploitation (Pęksa 2010, 2013; Pociask-Karteczka, Ed. 2013).

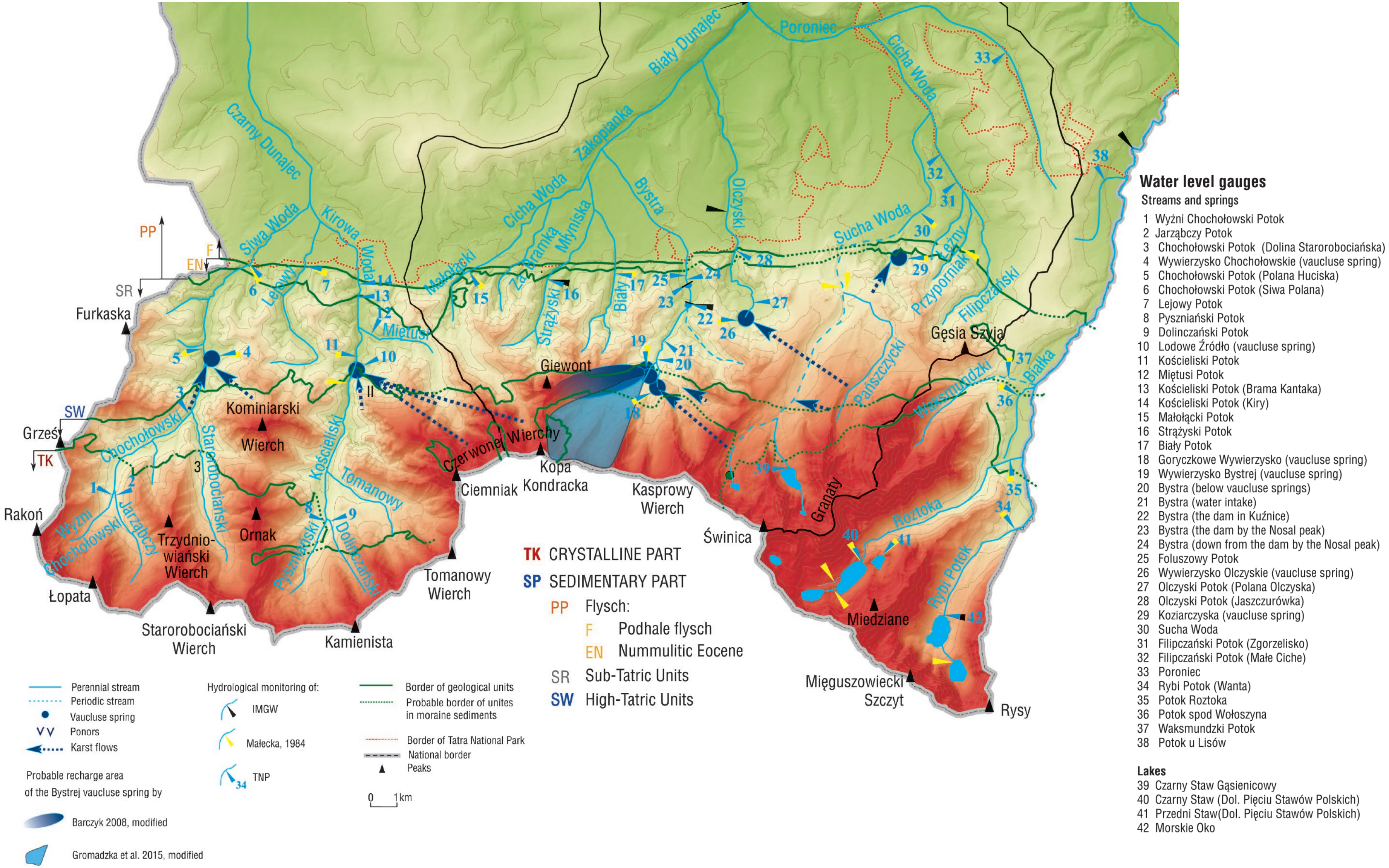

Fig. 5.1. Location of water gauging sites and karst flows (Barczyk 2008; Dąbrowski, Głazek 1968; Gromadzka et al. 2015; Łajczak 1996; Małecka 1984; Pęksa 2010; Żelazny 2012; modified).

River runoff regime

The Tatra Mountains streams are characterized by a simple hydrologic regime with one flood season, with the exception of Poroniec stream. Flood season occurs from April to July. Summer half-year runoff volume (May–October) is between 60% and 75% of the total annual river runoff. The highest discharge is recorded in May and June, especially when snowmelt is accompanied by rainfall that helps accelerate the melting of snow. High discharge in the snowmelt season lasts long enough in many catchments that it becomes superimposed upon the higher summer discharge period, especially in July when it is caused by rainfall (Łajczak 1996; Pociask-Karteczka et al. 2010, 2018; Żelazny et al. 2015d, 2016).

The low discharge period (passive period) usually lasts from August to March and sometimes is interrupted by somewhat higher discharge in autumn (Żelazny et al. 2016). The passive period is characterized by a partial stoppage in water circulation due to the accumulation of water in the snow cover (Łajczak 1996).

The most variable discharge over the annual cycle is found in small streams in the crystalline part of the Tatra Mountains: Waksmundzki Potok, Rybi Potok, Roztoka, and Dolinczański Potok, as well as in larger streams such as Kościeliski Potok and Chochołowski Potok (Fig. 5.2). The streams above are characterized by extremely low runoff in autumn and winter – caused by lack of precipitation and a very low groundwater supply due to poor groundwater aquifers in the crystalline

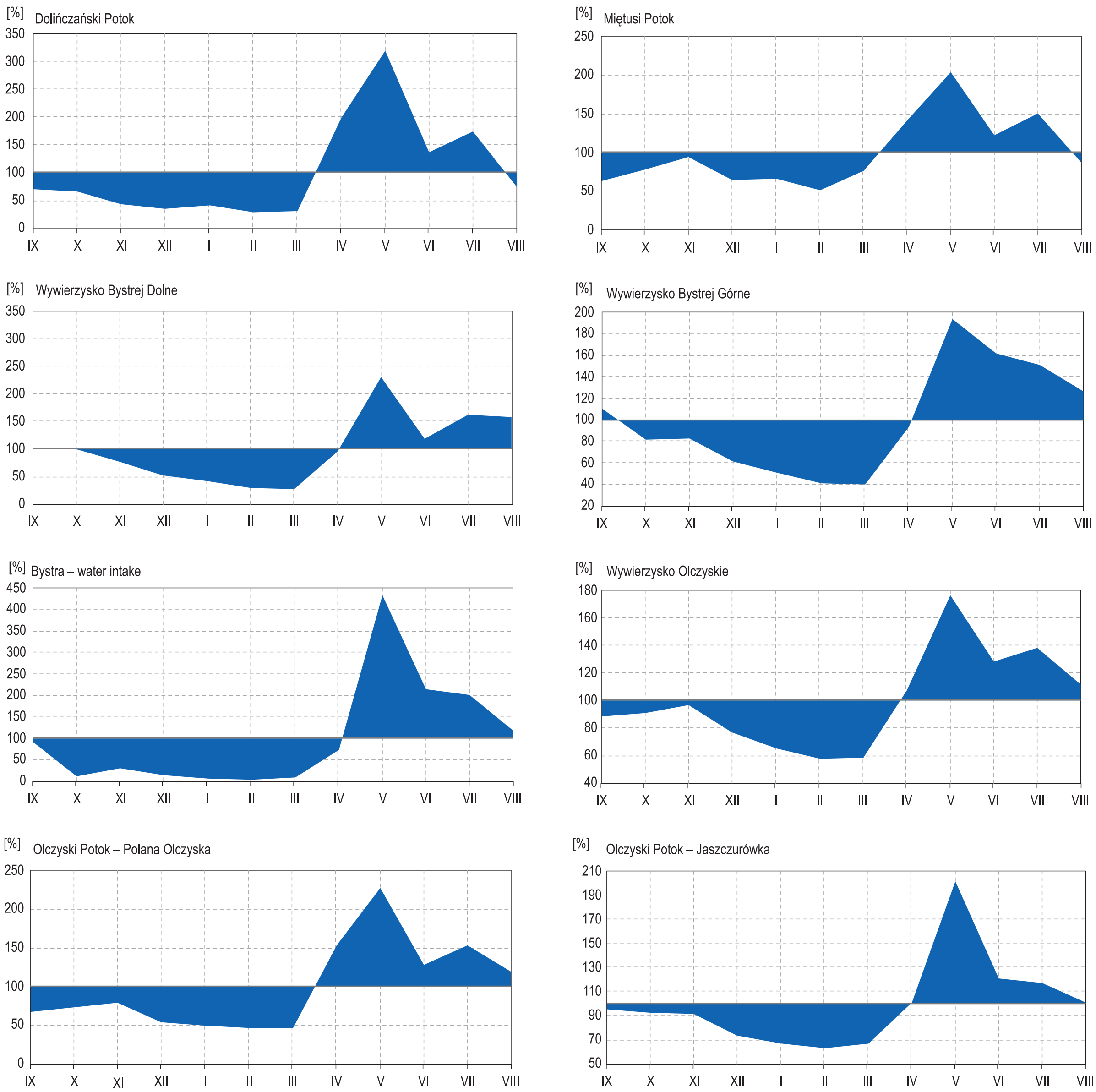

Fig. 5.2. Contribution of mean monthly discharge to the mean annual discharge of streams and springs in 2012–2014 (Żelazny et al. 2013, 2014, 2016, modified).

rocks. The least variable discharge over the annual cycle is noted in streams within the sedimentary part of the Tatra Mountains within Low-Tatric and High-Tatric Units (Lejowy Potok, Małołącki Potok, Miętusi Potok, and Filipczański Potok streams), as well as in streams recharged by vaucluse springs (Bystra, Olczyski Potok, Sucha Woda). The discharge in these streams remains quite high even in autumn and winter. The higher the discharge of the spring, the greater the impact on the stream. This pattern may be observed in the Olczyski Potok stream where the stream regime and spring regime are virtually identical. However, water intakes for household use in Zakopane in the downstream section leads to large variability in discharge downstream of water intakes (Fig. 5.2; Żelazny et al. 2015d, 2016).

Springs[1]

The mean density of springs in the Polish Tatra Mountains is 4.8 springs·km^{-2} and this value has been stable since the 1950s (Ziemońska 1966, Żelazny 2012). The density of spring reaches locally even 16 springs·km^{-2}, as in the Morskie Oko lake catchment (Pociask-Karteczka, Bochenek 2014). Most springs (85.2%) has a very low discharge – less than 1.0 $dm^3 \cdot s^{-1}$ (Photo. 5.1). The share of high discharge springs over 10 $dm^3 \cdot s^{-1}$ is very small at 1.5%, with five being vaucluse springs with discharge at more than 100 $dm^3 \cdot s^{-1}$. Vaucluse springs play the most significant role in the formation of water resources in the the Tatra Mountains. The discharge of five vaucluse springs is 1760 $dm^3 \cdot s^{-1}$, i.e. 65% of discharge of all springs in the Polish Tatra Mountains, which equals 2726 $dm^3 \cdot s^{-1}$ (Fig. 5.3). This is the equivalent of a specific runoff of 12.9 $dm^3 \cdot s^{-1} \cdot km^{-2}$ (i.e. 406 mm). The highest spring discharge is noted in the Bystra catchment – this equals 767 $dm^3 \cdot s^{-1}$. This is 28.1% of the total runoff of all springs in the Tatra Mountains (Figs. 5.4, 5.5). A higher spring discharge and

Photo. 5.1. The moraine spring in the upper part of the Bystra stream catchment (Photo. M. Żelazny).

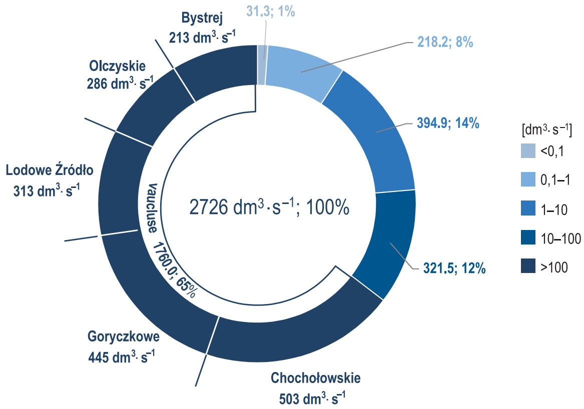

Fig. 5.3. Percent share of discharge from springs of particular discharge ranges (Żelazny 2012, modified).

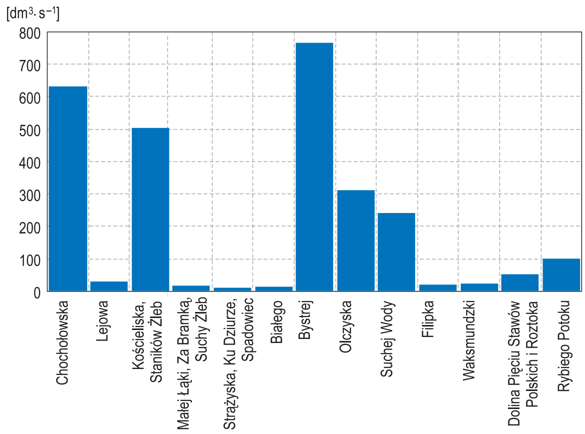

Fig. 5.4. Total spring discharge in the Tatra Mountains catchments (Żelazny 2012, modified).

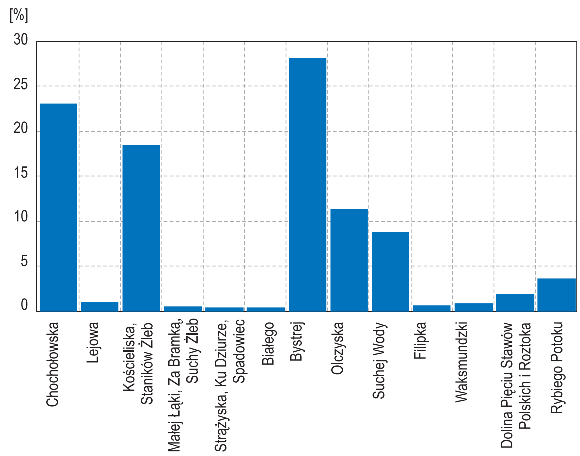

Fig. 5.5. Share of spring discharge in water resources in particular catchments of the Tatra Mountains (Żelazny 2012, modified).

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1 Research was carried out in the project N 30508132-2824 "Factors determining spatial variability and dynamics of water chemical composition in the Tatra National Park" funded by the Ministry and Higher Education, carried out from 2007 to 2010 (supervised by Mirosław Żelazny).

a little lower share of spring water resources are noted in the following stream catchments: Chochołowski Potok (respectively 631.6 $dm^3 \cdot s^{-1}$ and 23.17%), Kościeliski Potok (respectively 503.4 $dm^3 \cdot s^{-1}$ and 18.47%), and Olczyski Potok (respectively 311.7 $dm^3 \cdot s^{-1}$ and 11.43%). The lowest discharge and lowest share of total spring water resources are noted in the following stream catchments: Strążyski Potok, Potok ku Dziurze, and Spadowiec (respectively 12.8 $dm^3 \cdot s^{-1}$ and 0.47%), Małałołącki Potok, Potok za Bramką, Suchy Żleb (respectively 16.4 $dm^3 \cdot s^{-1}$ and 0.60%), Filipka (respectively 19.9 $dm^3 \cdot s^{-1}$ and 0.73%, Żelazny 2012).

The largest spring water resources expressed as total specific runoff of all springs occur in the following catchments: Olczyski Potok (67.9 $dm^3 \cdot s^{-1} \cdot km^{-2}$), somewhat smaller in Bystra (42.2 $dm^3 \cdot s^{-1} \cdot km^{-2}$), and many times smaller in the following catchments: Chochołowski Potok (18.3 $dm^3 \cdot s^{-1} \cdot km^{-2}$) and Kościeliski Potok (13.6 $dm^3 \cdot s^{-1} \cdot km^{-2}$; Fig. 5.6). Specific runoff noted in the catchments built of sedimentary rocks (16.9 $dm^3 \cdot s^{-1} \cdot km^{-2}$) is almost four times higher than that in areas formed of crystalline rocks (4.9 $dm^3 \cdot s^{-1} \cdot km^{-2}$; Fig. 5.7, Żelazny 2012).

The largest spring water resources are in the area below 1200 m a.s.l., where the total spring runoff reaches at 2227 $dm^3 \cdot s^{-1}$, which equals 81.7% of all water resources in the Polish Tatra Mountains (Fig. 5.8). There are three altitudinal belts with very high spring discharge rates: 950–1000 m a.s.l., 1050–1100 m a.s.l. and 1150–1200 m a.s.l. The first belt features 61 springs delivering 972 $dm^3 \cdot s^{-1}$ (35.7% of the water resources of the Polish Tatra Mountains, Fig. 5.9). This belt includes two large vaucluse springs in the Tatra Mountains, Wywierzysko Chochołowskie, which yields 503 $dm^3 \cdot s^{-1}$ as well as Lodowe Źródło, which yields 313 $dm^3 \cdot s^{-1}$. The belt from 1050 and 1100 m a.s.l. features 86 springs with a total discharge of 336.8 $dm^3 \cdot s^{-1}$ (12.4% of the water resources of the Polish Tatra Mountains). This belt also includes the large vaucluse spring i.e. Wywierzysko Olczyskie (286 $dm^3 \cdot s^{-1}$). Discharge of

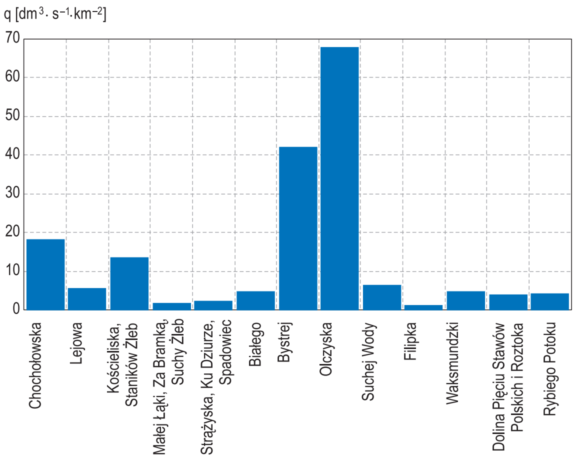

Fig. 5.6. Specific discharge of springs in the Tatra Mountains stream catchments (Żelazny 2012, modified).

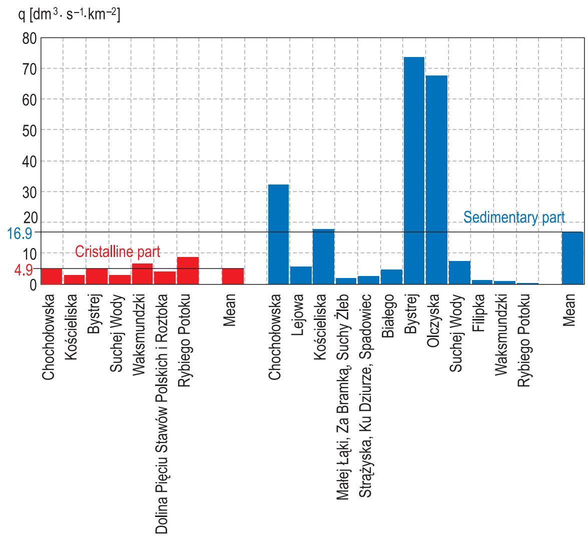

Fig. 5.7. Specific discharge of springs in the Tatra Mountains valleys versus local geology (Żelazny 2012, modified).

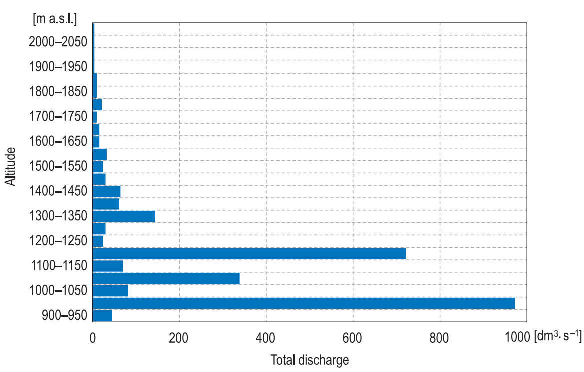

Fig. 5.8. Total spring discharge in selected altitudinal belts in the Tatra Mountains (Żelazny 2012, modified).

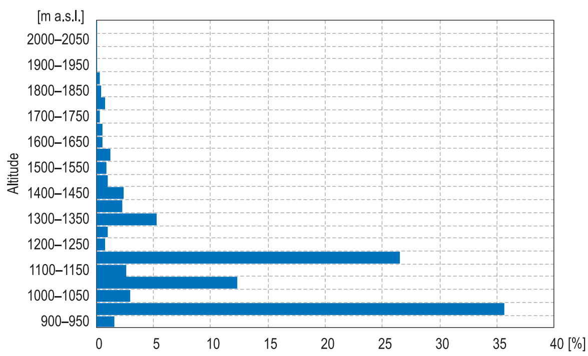

Fig. 5.9. Share of total spring discharge in total water resources in selected altitudinal belts in the Tatra Mountains (Żelazny 2012, modified).

86 springs in the third belt equals 721.5 $dm^3 \cdot s^{-1}$ i.e. 26.5% of the total discharge of all springs in the Polish Tatra Mountains. This zone includes two vaucluse springs: Wywierzysko Goryczkowe (445 $dm^3 \cdot s^{-1}$) and Wywierzysko Bystrej Dolne (213 $dm^3 \cdot s^{-1}$), both in the Bystra catchment (Żelazny 2012).

Water temperature regime

Surface water and groundwater of the Tatra Mountains exhibit a great variability of thermal regimes, which results from the presence of streams, vaucluse springs influence as well as lakes (Żelazny et al. 2015b). Maximum water temperature in lakes and streams occur frequently in August due to low water levels combined with increased atmospheric heating. In the case of vaucluse springs, maximum water temperatures are recorded in September. The highest stream water temperature (> 15°C) is observed in the Filipczański, Roztoka and Rybi. The average water temperature of streams is similar (4.9 ± 1.1°C). Minimum water temperature in streams occur frequently during the winter season, from December to March. In lakes, minima of water temperature usually occur between November and May. The highest minimum temperature are observed in karst springs and streams discharged by karst springs such as Bystra and Olczyski Potok (Żelazny et al. 2018).

Water temperature time series are characterized by the presence of several cycles such as daily, weekly, 8–30 days, half-yearly, and annual, which appear in seven different patterns. The Tatra Mountains lakes display a pattern with 8–30 days, half-yearly and annual cycles (Fig. 5.10). Vaucluse springs are characterized by two patterns with a) exclusively low-frequency components in the form of annual cycle, and b) less frequently both, annual and half-year cycles (Fig. 5.10). Vaucluse springs are characterized by relatively low and stable water temperature over the year. Small temperature amplitudes or even their lack indicate deep water circulation. One such example is the Lodowe Źródło vaucluse spring with an average water temperature of 4°C and annual water temperature amplitude never exceeding 1°C.

Streams represent four patterns with different complexity. Most often they are characterized by the lack of half-year cycle and the presence of daily and annual cycles (Fig. 5.10). The thermal regime of streams depends

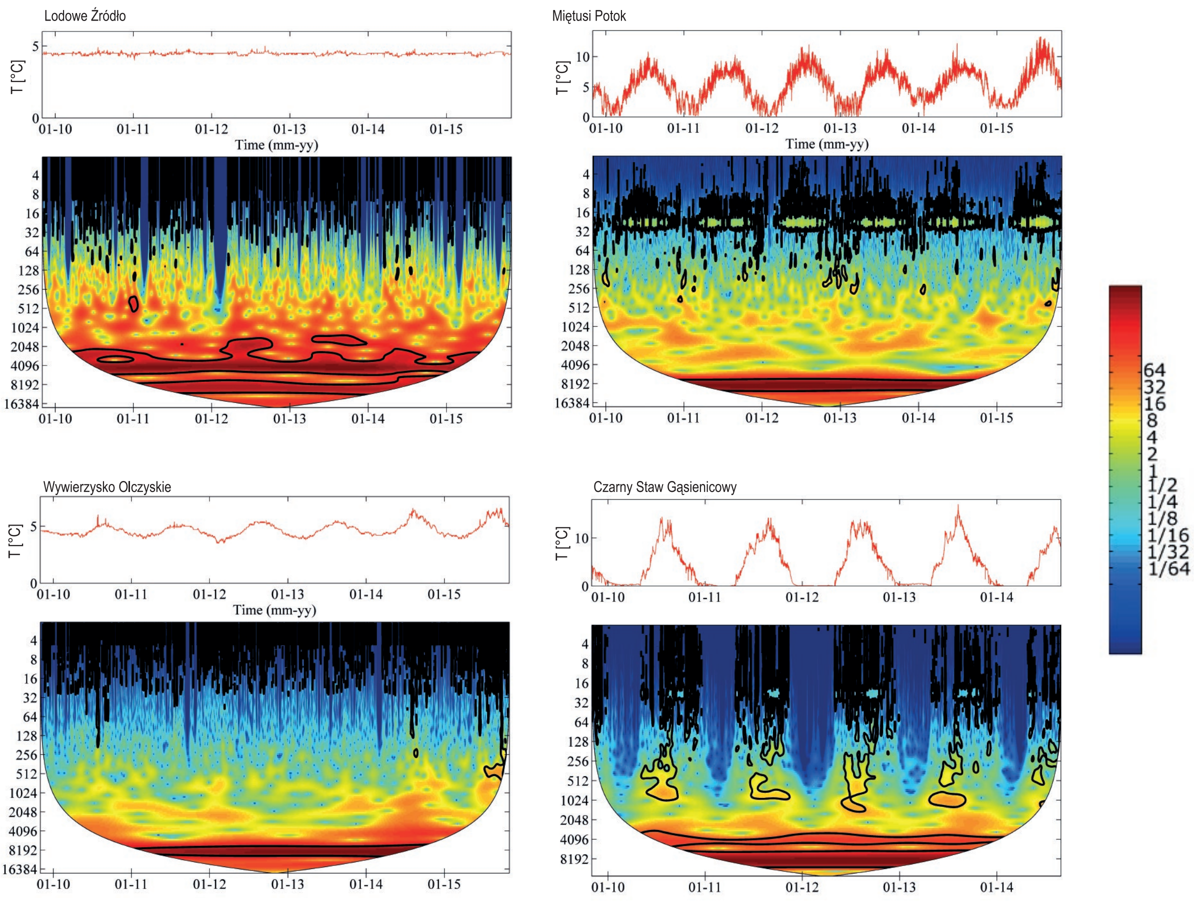

Fig. 5.10. Sample wavelet power spectra of water temperature time series (Żelazny et al., 2018). The upper plot shows the original time series of water temerature.

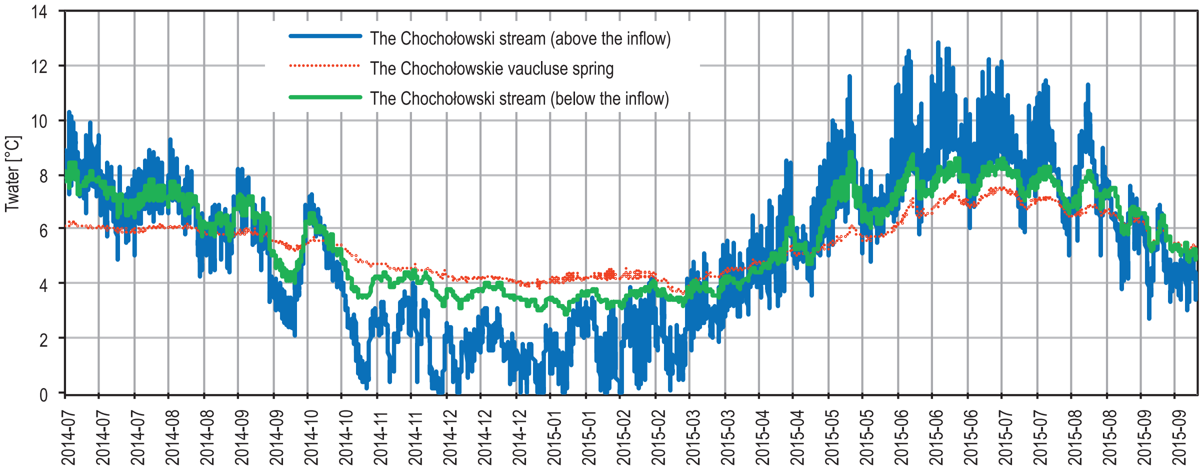

Fig. 5.11. Time series of water temperature in Chochołowski Potok stream (both upstream and downstream of water influx from the Wywierzysko Chochołowskie vaucluse springs) and Wywierzysko Chochołowskie vaucluse spring from January 2014 to September 2015 (Żelazny et al. 2018).

on cold water supply from snowmelt and groundwater. The latter diminish amplitudes of water temperature fluctuations and dampen daily cycles of water temperature. The dampening of daily cycle occurs especially in stream courses located directly below the inflow of karstic groundwater and gradually disappears with the distance from the karst water inflow. Moreover, vaucluse springs influence the energy budget of gaining streams (e.g. Chochołowski Potok, Kościeliski Potok, Bystra, Olczyski Potok and Sucha Woda) by cooling the stream water in summer and warming it in winter. The impact of groundwater on stream water temperature is clearly visible when comparing time series obtained from the Chochołowski Potok and the Chochołowskie vaucluse spring (Fig. 5.11).

The daily cycle occurring in water temperature time series is associated with air temperature, which in mountain conditions depends on the elevation above sea level. The annual cycle of water temperature is the most common and results from the seasonal changes in the temperate climate zone. The semi-annual cycle is associated with the presence of ice cover in lakes, which in fact, has significantly shortened over the last century. The 8–32 day cycle may be related to short periods of summer stratification that are preceded by equally short periods of spring turnover (Żelazny et al. 2018).

Surface water resources in The Tatra Mountains National Park in 2012–2014

Mean annual river runoff for 16 streams in the Tatra Mountains in the period 2012–2014 is 7.75 $m^3 \cdot s^{-1}$, which is the equivalent of 244.1 mln m^3 of water, while mean low discharge equals 2.026 $m^3 \cdot s^{-1}$, which is the equivalent of 63.8 mln m^3 of water (Tab. 5.1, Żelazny et al. 2013, 2014).

High specific runoff (> 50 $dm^3 \cdot s^{-1} \cdot km^{-2}$) occurs in catchments built of the High-Tatric units (crystalline part) including the catchments of the following streams: Pyszniański Potok (64.1 $dm^3 \cdot s^{-1} \cdot km^{-2}$), Rybi Potok (60.4 $dm^3 \cdot s^{-1} \cdot km^{-2}$), Wyżni Chochołowski Potok (55.7 $dm^3 \cdot s^{-1} \cdot km^{-2}$), Dolinczański Potok (54.7 $dm^3 \cdot s^{-1} \cdot km^{-2}$), and Goryczkowy Potok (51.8 $dm^3 \cdot s^{-1} \cdot km^{-2}$, Fig. 5.12). Specific runoff is lower in some of these catchments due to local geomorphologic and hydrogeologic conditions, as in the case of the following streams: Roztoka (42.5 $dm^3 \cdot s^{-1} \cdot km^{-2}$), Jarząbczy Potok (39.6 $dm^3 \cdot s^{-1} \cdot km^{-2}$), Waksmundzki Potok (39.0 $dm^3 \cdot s^{-1} \cdot km^{-2}$). Discharge in Jarząbczy Potok stream is reduced by water intake generated by a hydroelectric plant located near the tourist lodge in the Chochołowski Potok catchment. A river beds of the Roztoka and Waksmundzki Potok "lose" water, which is why it is reasonable to presume that the total water resources of these catchments are much larger. The analysis of water conditions appears that runoff in the crystalline part of the Tatra Moun-

Table 5.1. Water resources characteristisc in the Polish Tatra Mountains in 2012–2014 (Żelazny et al. 2013, 2014, 2016).

Characteristic	The Tatra Mountains (179.5 km^2)	
	mean	low
Runoff [$m^3 \cdot s^{-1}$]	7.75	2.03
Specific runoff [$dm^3 \cdot s^{-1} \cdot km^{-2}$]	43.2	11.3
Runoff index [mm]	1360	356
Volume [milion m^3]	244.1	63.8

tains is strongly divided into two parts: (1) Western Tatra Mountains, (2) High (eastern) Tatra Mountains. The western part is characterized by higher specific runoff (53.4 $dm^3 \cdot s^{-1} \cdot km^{-2}$) than the eastern part (48.4$dm^3 \cdot s^{-1} \cdot km^{-2}$). However, the High Tatra Mountains are characterized by a larger total amount of water resources than the Western Tatra Mountains due to their larger surface area (29.2 km^2 and 16 km^2, respectively, Tab. 5.2; Żelazny 2015e).

Table 5.2. Stream water resources characteristisc in the High-Tatras units of the Tatra Mountains in 2012–2014 (Żelazny et al. 2013, 2014, 2016).

Characteristic	High Tatra Mountains (29.2 km^2)		West Tatra Mountains (16 km^2)	
	mean	low	mean	low
Specific runoff [$dm^3 \cdot s^{-1} \cdot km^{-2}$]	48.4	9.4	53.4	11.0
Runoff index [mm]	1524	297	1681	245
Volume [milion m^3]	44.5	8.6	26.9	5.5

The Tatra Mountains built of Sub-Tatric Units are characterized by lower water resources and this includes catchments such as those of the following streams: Małołącki Potok (18.6 $dm^3 \cdot s^{-1} \cdot km^{-2}$), Filipczański Potok (23.9 $dm^3 \cdot s^{-1} \cdot km^{-2}$), Biały (26.1 $dm^3 \cdot s^{-1} \cdot km^{-2}$), Lejowy Potok (27.7 $dm^3 \cdot s^{-1} \cdot km^{-2}$), Strążyski Potok (29.1 $dm^3 \cdot s^{-1} \cdot km^{-2}$), Sucha Woda (20.4 $dm^3 \cdot s^{-1} \cdot km^{-2}$), Poroniec (43.7 $dm^3 \cdot s^{-1} \cdot km^{-2}$, Fig. 5.12). On the other hand, very high resources are found in catchments with large vaucluse springs having recharge area beyond the topographic catchments, as shown by Małecka (1993). Examples of catchments of high specific runoff include the following:

- Olczyski Potok (92.9 $dm^3 \cdot s^{-1} \cdot km^{-2}$) – recharge area in the Pańszczyca catchment (crystalline part),
- Bystra (75.1 $dm^3 \cdot s^{-1} \cdot km^{-2}$) – recharge area in the Sucha Woda catchment (crystalline part),
- Kościeliski Potok (57.1 $dm^3 \cdot s^{-1} \cdot km^{-2}$) – recharge area in the Czerwone Wierchy massif (sedimentary part),
- Potok u Lisów (86.1 $dm^3 \cdot s^{-1} \cdot km^{-2}$),
- Potok spod Wołoszyna (73.7 $dm^3 \cdot s^{-1} \cdot km^{-2}$).

Hydrology of the Bystra stream catchment

The Bystra stream is a tributary of Zakopianka – a right-hand tributary of Białka flowing towards the Dunajec river – the right-hand tributary of the Vistula river. The Bystra stream catchment is located on the border between the Western and the High Tatra Mountains (Photo. 5.2). The highest point of the area is the Kondracka Kopa (2004 m a.s.l.). The water level gauge is located at the elevation of 955 m a.s.l. The average slope is 26.8°. The Bystra stream catchment is characterized by a particularly complex geological and tectonic structure. The northern part of the catchment is built of sedimentary rocks of the Sub-Tatric Units, which include dolomite, limestone, and shale (Bac-Moszaszwili et al. 1979, Piotrowska et al. 2015). The southern part is built of crystalline rocks and is divided into western and eastern parts. The western part (with Kondratowa Hala clearing) has no permanent watercourses, small number of springs of low discharge reaching 0.5 $dm^3 \cdot s^{-1}$. The eastern part (with the Goryczkowy Potok stream) features relatively high discharge springs reaching 10.0 $dm^3 \cdot s^{-1}$ and a permanent watercourse that disappears in a ponor in the area of the Hala Goryczkowa clearing (Fig. 5.13). The southern and middle parts of the catchment were strongly transformed by glaciers, which led to the formation of glacier cirques and thick moraine formations (Klimaszewski 1988). Moreover, there are numerous karst phenomena such as ponors, caves, and vaucluse springs in the middle part of the catchment (Barczyk 2008; Dąbrowski, Głazek 1968; Małecka 1997; Wit-Jóźwik, Ziemońska 1960a; Wrzosek 1933). Research on the water balance in the Tatra Mountains has shown that the runoff-rainfall ratio for the Bystra catchment is 1.04,

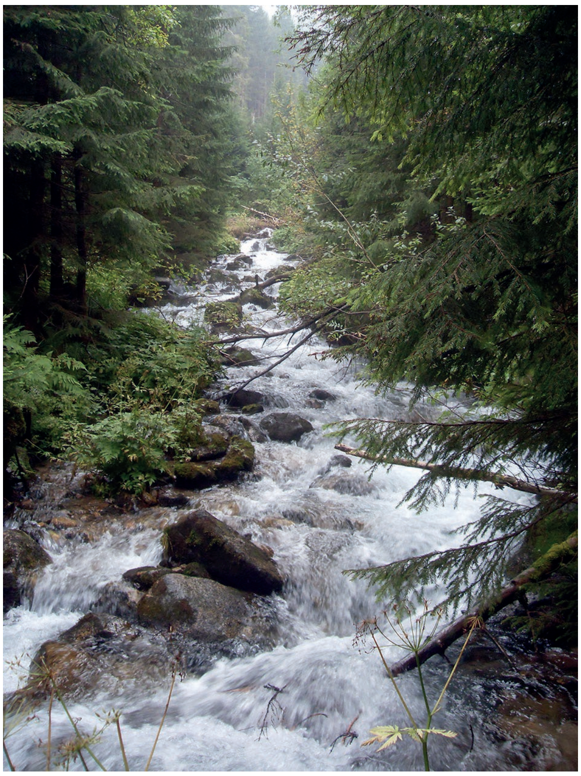

Photo. 5.2. The Bystra stream in the middle course (Photo. J. Pociask-Karteczka).

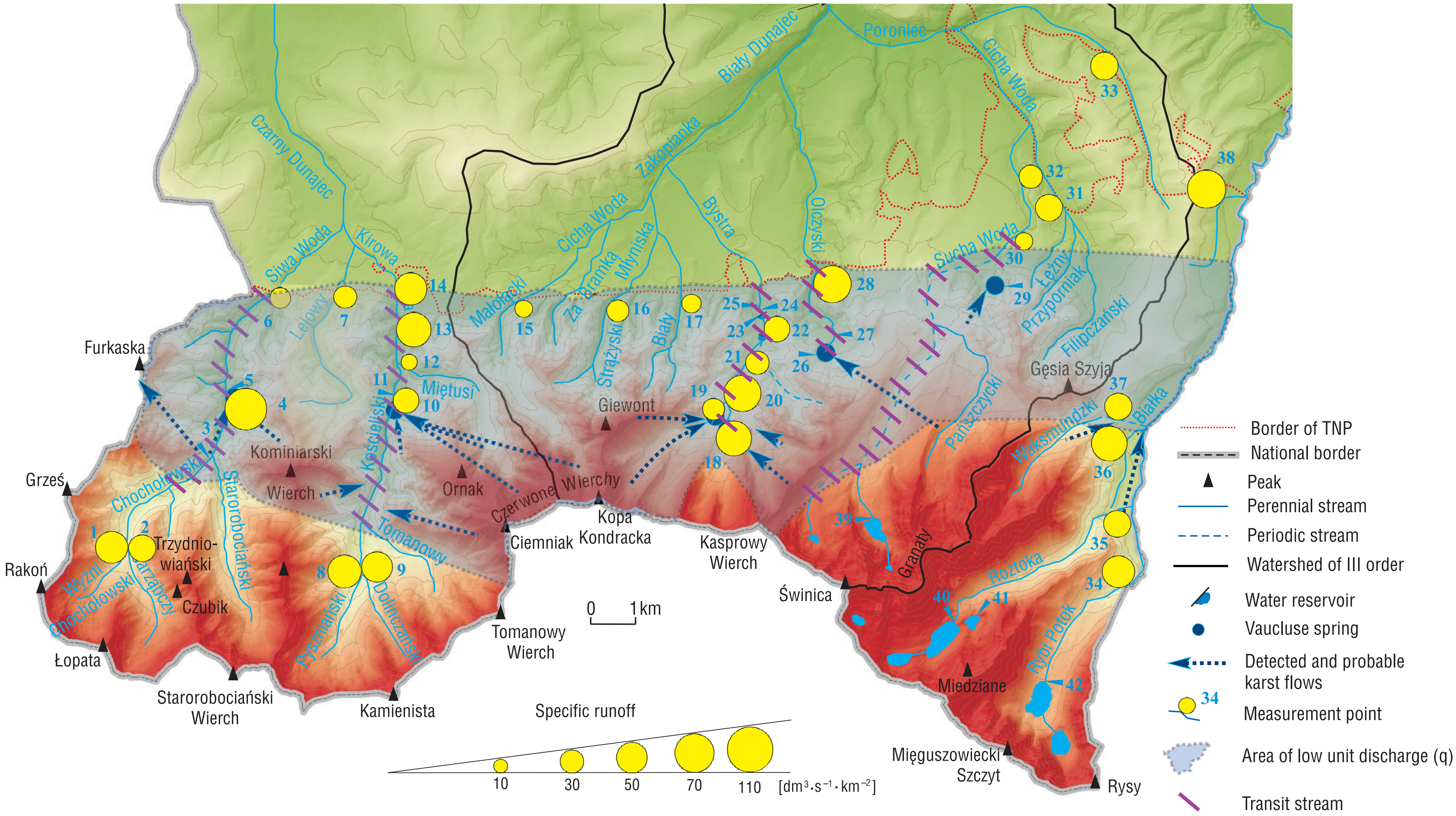

Fig. 5.12. Water resources expressed in specific runoff in the Polish Tatra Mountains in 2013 (Barczyk 2008; Dąbrowski, Głazek 1968; Gromadzka et al. 2015; Łajczak 1996; Małecka 1984; Pęksa 2010; Żelazny 2012; Żelazny et al. 2013, 2014, 2016; modified).

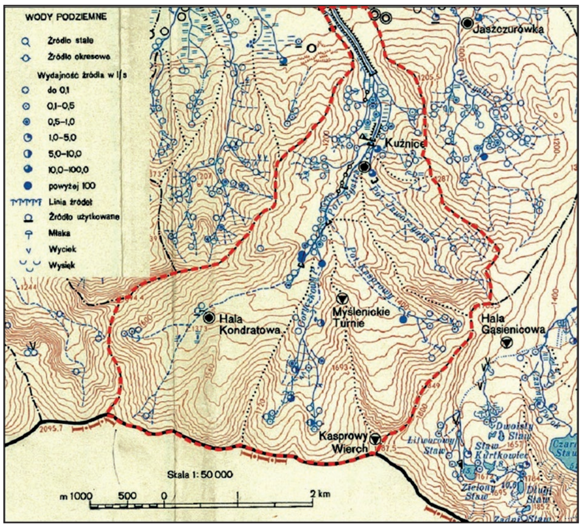

Fig. 5.13. Hydrologic map (red line – watershed of the Bystra stream catchment; Wit, Ziemońska 1960a, b, 1985).

which means that river runoff exceeds atmospheric precipitation (Małecka 1993, 1996). As it was mentioned before, the Bystra catchment is the second catchment, following the Olczyski Potok catchment, in terms of water resources in the Tatra Mountains. Its middle part includes one of the largest springs in Poland – Wywierzysko Goryczkowe vaucluse spring – with a discharge of about 700 $dm^3 \cdot s^{-1}$ (Małecka 1997). The recharge area of Wywierzysko Goryczkowe vaucluse spring is located beyond its topographic catchment – in the Sucha Woda catchment as shown in the 1960s by Dąbrowski and Głazek (1968) who used the dye-tracing technique.

The east slopes of the Giewont massif feature two vaucluse springs: Wywierzysko Bystrej Dolne and Wywierzysko Bystrej Górne (Photo. 5.3). The Wywierzysko Bystrej Górne vaucluse spring is an intermittent and virtually disappears in the winter, while the Wywierzysko Bystrej Dolne vaucluse spring is permanent (Barczyk 2008, Małecka 1997; Wit, Ziemońska 1960a, b). The total discharge of both springs is 321 $dm^3 \cdot s^{-1}$. According to Małecka (1997) and Barczyk (2008), the most likely recharge area of both springs is the Giewont massif and perhaps the eastern parts of the Czerwone Wierchy massif. However contemporary hydrochemical research has shown that the most likely recharge area is located in the Sucha Kondracka and Sucha Kondratowa subcatchments, because the total dissolved solids were not enough higher if the recharge area were located on the Giewont massif (Gromadzka et al. 2015). A third vaucluse spring appears south of the Wywierzysko Bystrej Górne vaucluse spring following heavy precipitation every dozen years or so.

Photo. 5.3. The Wywierzysko Bystrej Górne vaucluse spring (Photo. J. Pociask-Karteczka).

Anthropogenic pressure to use water in Bystra catchment for artificial snowing is significant, which makes it important to identify the amount of water resources available during wintertime low flow periods. Detailed studies of this problem have been conducted since 2013 and especial hydrographic network was established there. The highest, crystalline part of the Bystra catchment is drained by two streams: Potok Zakosy (5.5 $dm^3 \cdot s^{-1}$) and the stream at the Goryczkowa Rówień (1.9 $dm^3 \cdot s^{-1}$). The two streams then merge to form Goryczkowy Potok stream (Fig. 5.14), although its discharge is much smaller than that expected from the sum of the discharge values for the two contributing streams: 2.3 $dm^3 \cdot s^{-1}$. This is explained by the disappearance of water from Goryczkowy Potok stream into thick moraine formations and ponors. A complete disappearance of water in Goryczkowy Potok stream in fact was observed already in the 1950s in the downstream section of the catchment. More recent research has shown that water loss in the channel occurs in an upper section of the catchment – higher than what had been described by Wit and Ziemońska (1960a, b). Discharge of the Bystra stream increases abruptly in the middle part of the catchment due inflow of water from the Wywierzysko Bystrej Górne, Wywierzysko Bystrej Dolne, and Goryczkowe Wywierzysko vaucluse springs and reaches 996 $dm^3 \cdot s^{-1}$ (2010-2014). This is the equivalent of a specific runoff of 126.4 $dm^3 \cdot s^{-1} \cdot km^{-2}$, which gives it most likely the largest specific runoff in Poland (Tables 5.3, 5.4).

There have been observed a regular increase of the Bystra stream discharge in May in the period 2010––2015. The most regular pattern of minimum discharge has been observed in the winter time – January or February (Fig. 5.15). The longest low discharge period in 2010–2014 lasted from September 2011 to March 2012 (Fig. 5.16). However, the lowest discharge (244 $dm^3 \cdot s^{-1}$) was noted during the year 2014 winter

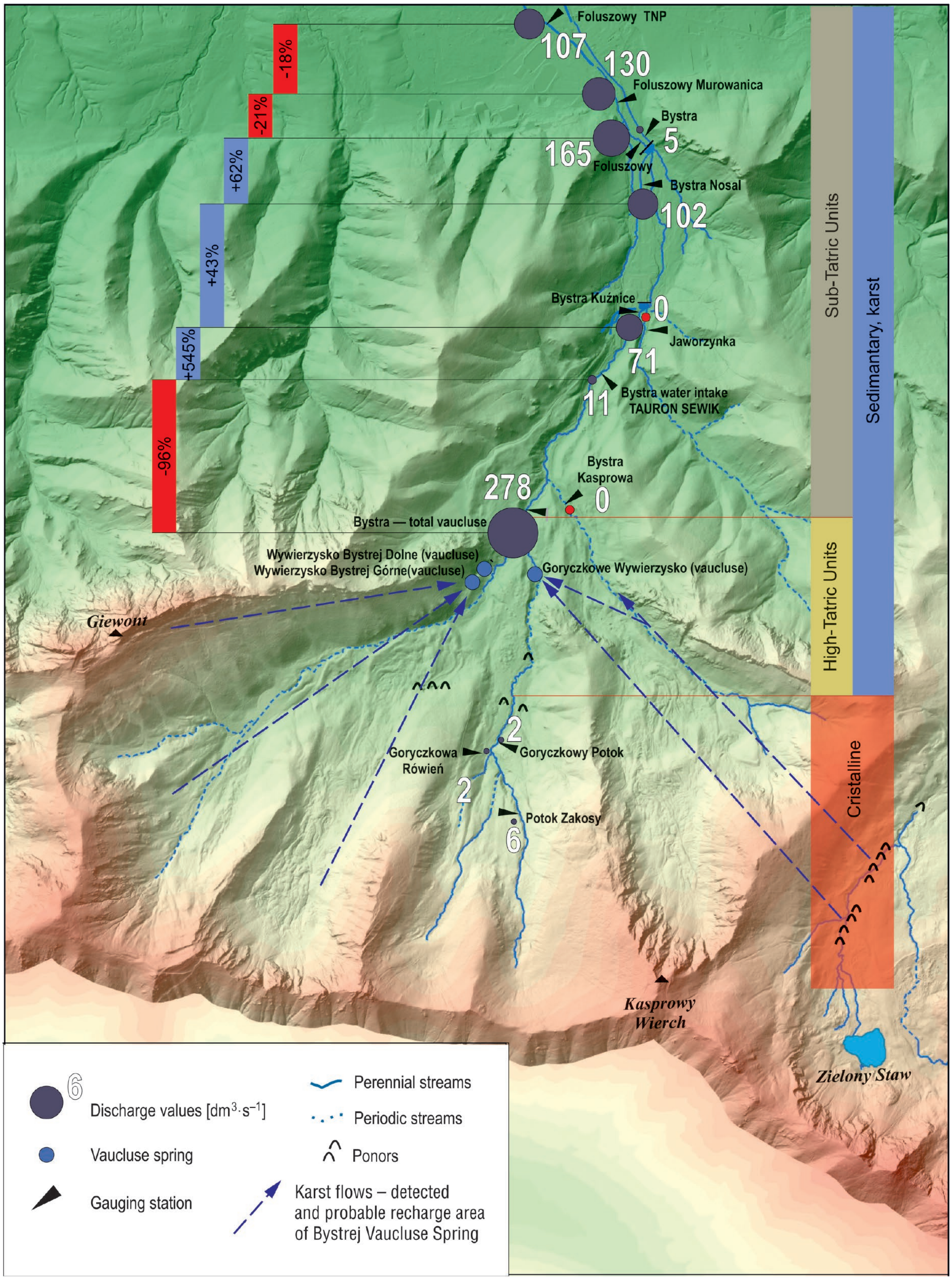

Fig. 5.14. Water resources along the longitudinal profile of Bystra stream on 16 January 2015 (Barczyk 2008; Dąbrowski, Głazek 1968; Gromadzka et al. 2015; Łajczak 1996; Małecka 1984; Pęksa 2010; Żelazny 2012; Żelazny et al. 2013, 2014, 2015a, 2016; Żelazny et al. 2013–2016; modified).

Table 5.3. Characteristics of the discharge of the Bystra stream below the vaucluse springs (Goryczkowe, Bystrej Górne, Bystrej Dolne) in the period 2010–2014 (Żelazny et al. 2015a).

Year	Discharge Q [$dm^3 \cdot s^{-1}$]							
	Q_{mean}	Q_{min}	Q_{max}	$Q_{25\%}$	$Q_{50\%}$	$Q_{75\%}$	$Q_{10\%}$	$Q_{90\%}$
2010	1119	291	3781	650	858	1448	469	2170
2011	803	291	2433	469	653	1088	379	1511
2012	875	335	2472	423	778	990	423	1774
2013	1049	423	2956	614	842	1314	514	1954
2014	1136	244	5982	469	911	1663	379	2105
Mean	996	317	3525	525	808	1301	433	1903

Table 5.4. Characteristics of specific runoff of the Bystra stream catchment below the vaucluse springs (Goryczkowe, Bystrej Górne, Bystrej Dolne) in the period 2010–2014 (Żelazny et al. 2015a).

Year	Specific runoff q [$dm^3 \cdot s^{-1} \cdot km^{-2}$]							
	q_{mean}	q_{min}	q_{max}	$q_{25\%}$	$q_{50\%}$	$q_{75\%}$	$q_{10\%}$	$q_{90\%}$
2010	142.0	36.9	479.8	82.5	108.9	183.8	59.5	275.4
2011	101.9	36.9	308.8	59.5	82.9	138.1	48.1	191.8
2012	111.0	42.5	313.7	53.7	98.7	125.6	53.7	225.1
2013	133.1	53.7	375.1	77.9	106.9	166.8	65.2	248.0
2014	144.2	31.0	759.1	59.5	115.6	211.0	48.1	267.1
Mean	126.4	40.2	447.3	66.6	102.6	165.1	54.9	241.5

low flow period (specific discharge equivalent is 31 $dm^3 \cdot s^{-1} \cdot km^{-2}$; Tables 5.3, 5.4).

The human impact in the Bystra stream catchment increases downstream. As a result, discharge of the Bystra stream declines significantly (by even 96%, Fig. 5.14). A regular daily cycle of water use may be observed – less water is used at night leading to higher discharge at night time, and more water is used in daytime, especially around noon and in the afternoon hours (Fig. 5.17). The discharge of the Bystra stream increases to 71 $dm^3 \cdot s^{-1}$ in Kuźnice where it runs in a stone-laden channel (while the discharge of the Bystra stream rechaes 278 $dm^3 \cdot s^{-1}$ in the upper course). There are also three spring water intakes at Kuźnice in the lower part of the Bystra catchment (Gonciska, Jedle, and Kórnickie). The Bystra stream divides in Kuźnice down of the dam build of granitic rocks: Bystra flows down in a stony channel and another creek – known in Zakopane as Foluszowy Potok – flows partly in a moraine material and stony channel.

Hydrologic regions

Two hydrographic regions have been identified in Tatra National Park based on local geology, which determines water circulation patterns as well as groundwater and surface water supply levels in the Park (Fig. 5.18):

- the Tatra Mountains region (I),
- flysch region (II).

The Tatra Mountains region consists of three subregions (Ziemońska 1966, Siwek et al. 2015, Żelazny et al. 2015b):

- crystalline subregion (Ia),
- high mountain, karst, limestone, dolomite region (Ib),
- dolomite, shale, middle mountain region (Ic).

Crystalline subregion (Ia) is characterized by shallow water circulation and high water retention across the valley bottom in moraine formations and glacial lakes. Due to its high elevation above sea level, the region receives the highest amounts of precipitation, mostly in the form of snow. High mountain, karst, limestone, dolomite region (Ib), with developed karst system allows for substantial water retention and migration of groundwater as well as the occurrence of large groundwater aquifers. The significant discrepancy in size of the hydrogeological and topographical catchment is very common characteristic for vaucluse karst springs located in this region. Ponors, dry river channels, periodic and intermittent streams are typical here. The region at the lowest altitude, is the dolomite and shale region (Ic), which is characterized by shallow water circulation, a well-developed

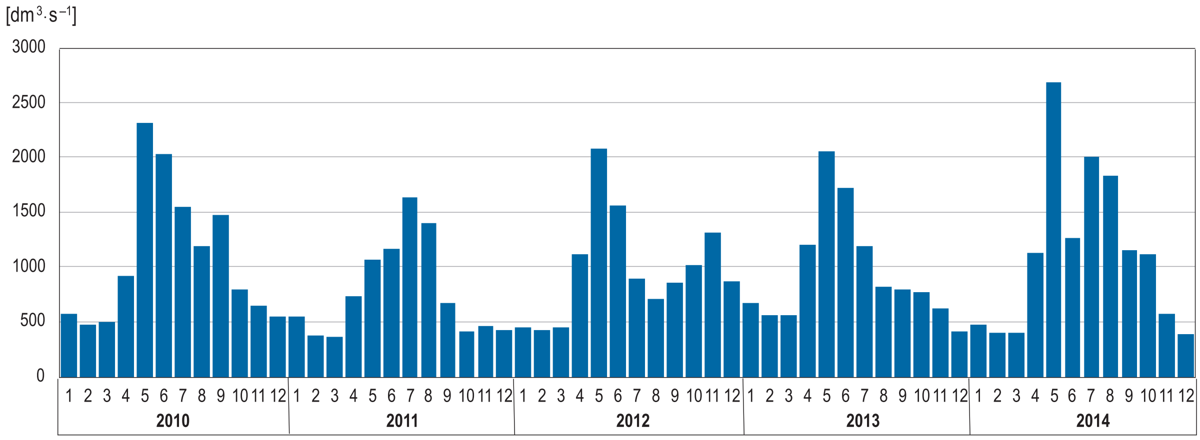

Fig. 5.15. Mean monthly discharge of Bystra downstream of the vaucluse springs in the period 2010–2014 (Żelazny et al. 2015a, modified).

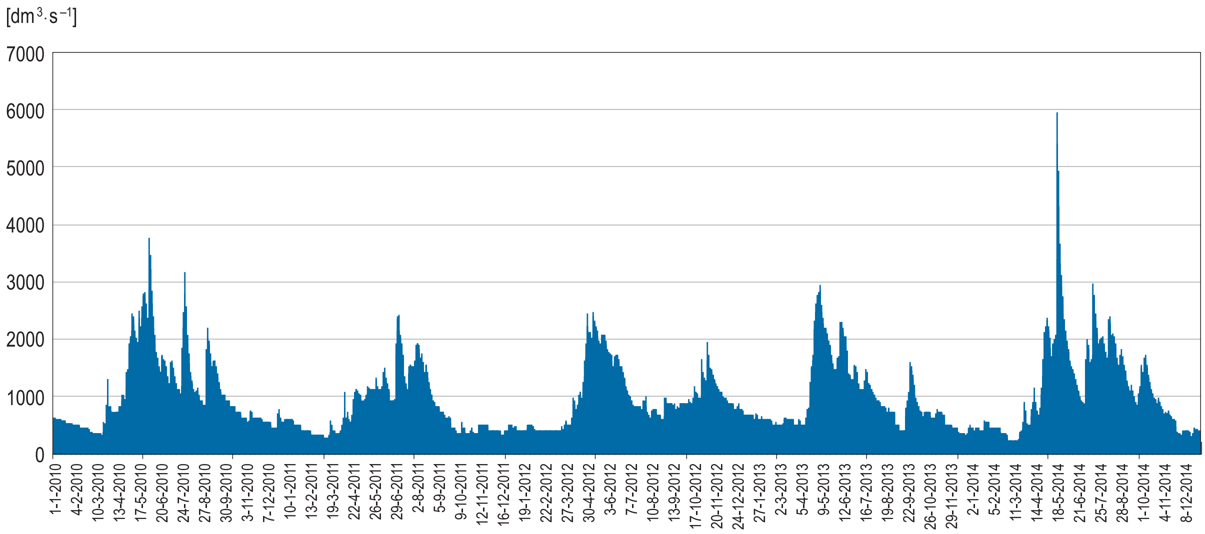

Fig. 5.16. Daily discharge of Bystra downstream of the vaucluse springs in the period 2010–2014 (Żelazny et al. 2015a).

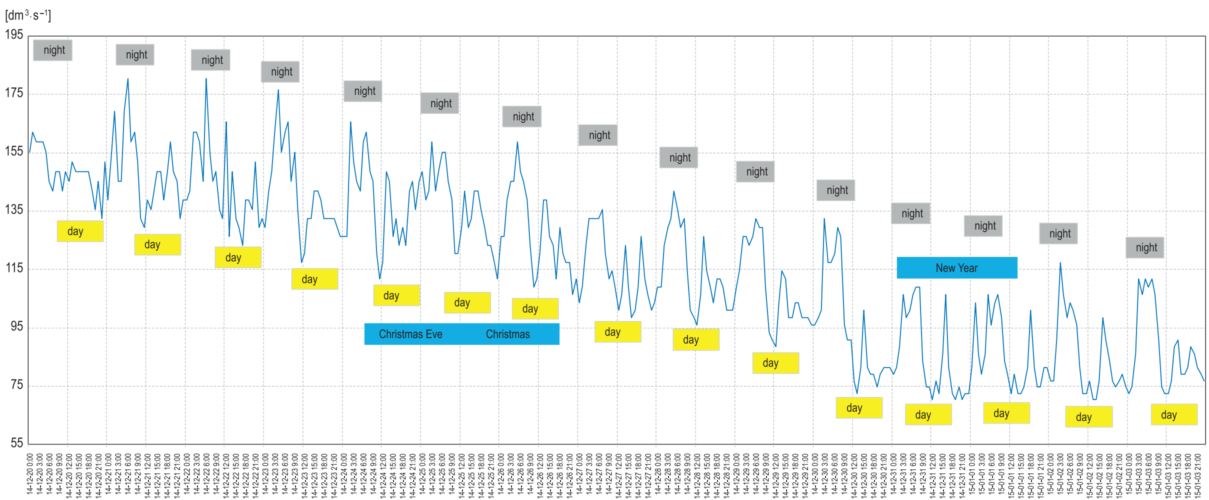

Fig. 5.17. Diurnal changes in discharge of Bystra stream at Kuźnice gauging station from December 2014 to January 2015 (Żelazny et al. 2015a).

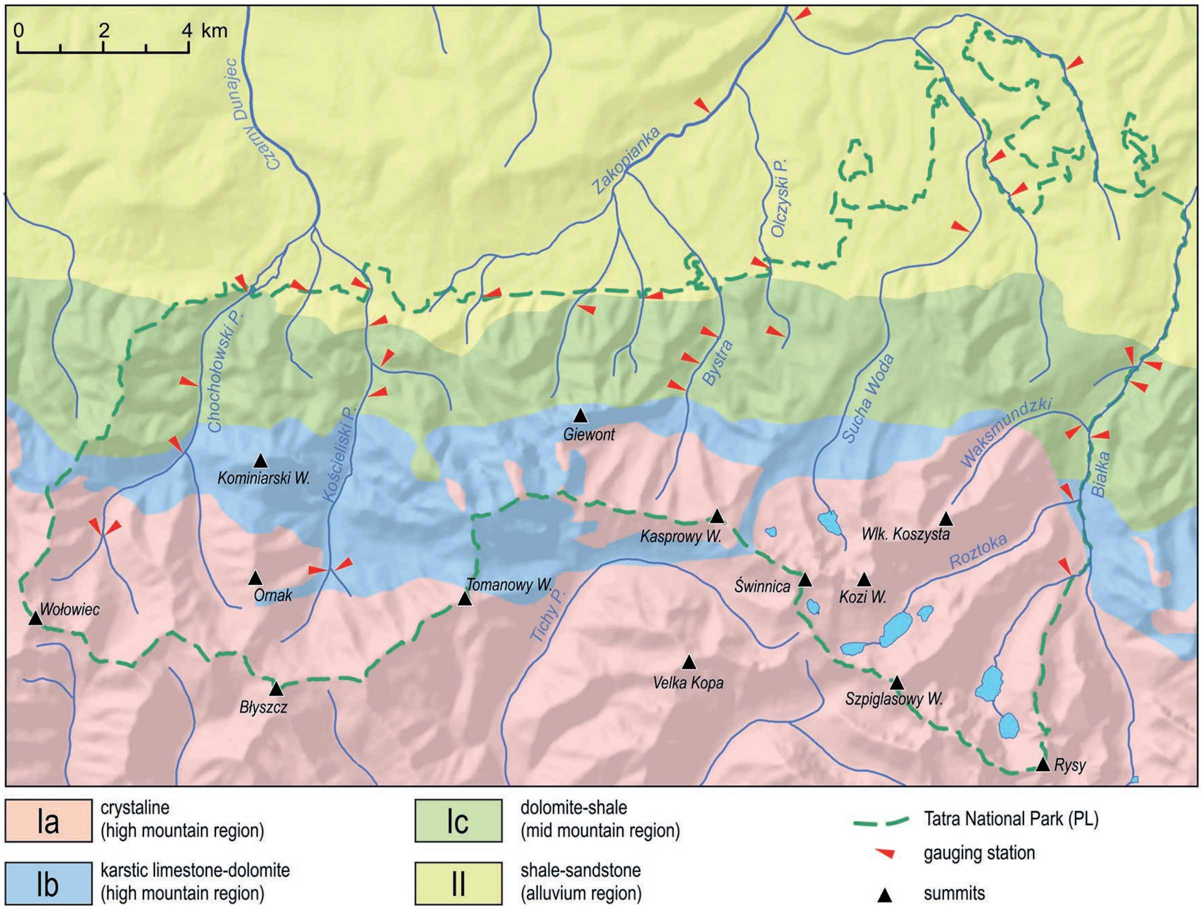

Fig. 5.18. Hydrographic regions in the Tatra Mountains (Ziemońska 1966, Żelazny et al. 2015c, modified).

river network, and a presence of numerous springs of low discharge.

The flysch region (II) is located across the Tatra Mountains foreland, and is primarily formed of sandstone and shale. It is a hydro-geologically distinct environment, but recharge areas of flysch formations also include parts of the Tatra Mountains region.

One of the key parameters indicating water resources level is the contribution of base flow in river runoff. Catchments characterized by a high base flow tend to be particularly valuable for water use purposes, as they are less sensitive to seasonal changes in hydro-meteorological conditions. The contribution of base flow in the Tatra Mountains river runoff is between 30% and 55% and it tends to be the highest in catchments with a relatively high carbonate rock content (subregion Ib) as well as in catchments with substantial thickness of fluvioglacial cover and moraine cover including gravel and sand (Żelazny et al. 2015c).

Chapter 6

Management and protection of water resources in the Tatra National Park

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Abstract: Water resources in the Tatra National Park are essential for community living in Zakopane and its vicinity, and for functioning mountain lodges located in the Park. Surface freshwater and groundwater intakes occur in the majority of mountain creek catchments and covers the water requirements for domestic and public services in mountain lodges, for electric power plants both in and out of the Park, and for artificial snowing. The quality of water is high, and thus does not require advanced treatment techniques. In summer months, and September and October, water consumption is the biggest and is associated with tourist traffic in Zakopane. Water monitoring system developed by the Tatra National Park in the beginning of the 20th century, provides data for more accurate water resource management. Another vital practice which assists in helping to preserve water resources and ecosystems in the Tatra National Park is ecological education. Contemporary water resources extraction in the Tatra National Park tends to be sustainable, however the increasing demand for water in the region, especially for artificial snowing, instigates conflict between the Park (nature protection) and touristic, and ski lobbies (exploitation of water).

Keywords: water intakes, hydropower, artificial snowmaking, ecological education

INTRODUCTION

Water ecosystems make up 7.1% of the total area of Poland's national parks, however within the Tatra National Park total coverage does not exceed 1% (Partyka, Pociask-Karteczka 2008). Nevertheless streams, springs, lakes, marshlands and wetlands are important elements of mountainous landscape, they influence biodiversity in the natural environment.

The Tatra Mountains were initially explored by semi-nomadic herdsmen and gold prospectors in the Middle Ages, but the negative human impact on the environment was insignificant (Pociask-Karteczka 2009). As time passed, the human pressure on the environment – and subsequently on water resources – became stronger (Fig. 6.1). As shown the increasing of sheep herding in the 18th century resulted in the need for more areas for pasture and, the unrestrained development of the mining and iron industry required large amounts of wood and water. Moreover, the accessibility, beauty and uniqueness of the Tatra Mountains make them an important tourist destination and thus, caused a rapid increase intourism, especially after the Second World War, which led to further changes in the natural composition of the region. Water resources of the Tatra Mountains have become a main source of municipal water for Zakopane, which is located in the mountain's foreland. The establishment of National Park status in the Polish Tatra Mountains in 1954, stopped most of these exploational processes with the exception of the utilisation of mountainous water sources. This is mostly due to the reliance on these resources by the Zakopane community and the mountain lodges located within the Park itself.

There are various forms of groundwater and surface water supplies in the Tatra National Park. Types

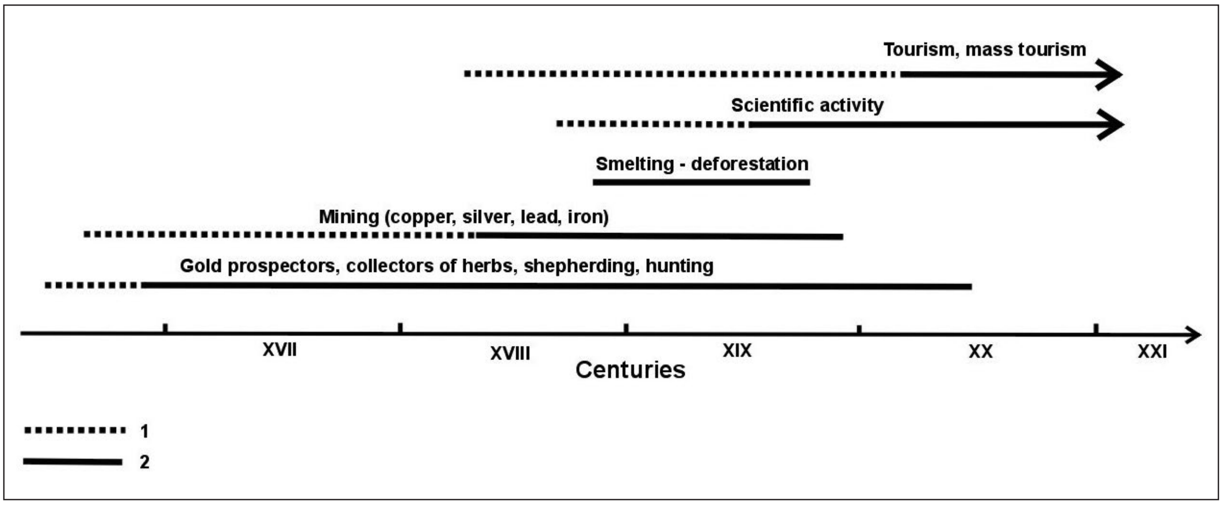

Fig. 6.1. Human activities influenced changes in nature of the Tatra National Park over centuries (1 – weak activity, 2 – strong activity; Pociask-Karteczka 2009).

of surface water stores include lakes, rivers, wetlands and snow cover (in winter). In summer, some freshwater resources can be found in snow patches at high altitudes. The abundance of water is influenced by climatic conditions – changing according to vertical belts (Hess 1974). All elements of water balance (precipitation, runoff, evapotranspiration) change with the altitude above sea level. Furthermore, temporal changes in the location of vertical climatic belts have been observed and they are a result of current climate change (Łupikasza, Szypuła 2018).

Springs, creeks and lakes

There are numerous springs located in the Tatra National Park. The discharge of the most of ap. 900 springs does not exceed 1 $dm^3 \cdot s^{-1}$. There are 102 springs of discharge 1–10 $dm^3 \cdot s^{-1}$ and 21 springs with discharge exceeding 10 $dm^3 \cdot s^{-1}$ (Partyka, Pociask-Karteczka 2008). Vaucluse karst springs are the most abundant in water (Chochołowskie, Lodowe, Bystrej, Goryczkowe, Olczyskie). The maximum discharge occur during snowmelt (April–May) and rain periods (June–July, Photo. 6.1).

River network density in Tatra Mountains reach 0.94 $km \cdot km^{-2}$ in case of permanent watercourses (175 km) and 0.79 $km \cdot km^{-2}$ – in case of seasonal ones (147 km). Most of river channels is natural. However a short section of the Bystra creek has been straightened in a "stony channel" as a testimony of human activity in the 19th and 20th centuries. Flow alteration has an extensive and pervasive influence on a river's form and function, and significantly influence aquatic biota and ecosystem (Kot, Kot 2015; Zontag, Kot 2015).

There are two rivers of discharge exceeding 3 $m^3 \cdot s^{-1}$, i.e. Czarny Dunajec and Białka in the Tatra National

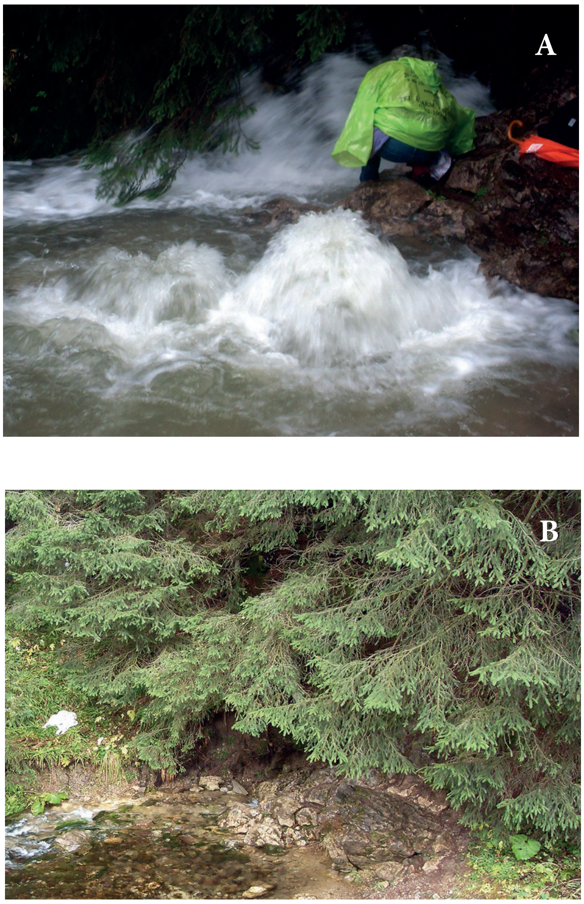

Photo. 6.1. The Olczyskie vaucluse spring: A – May 2014, season of snowmelt and rain precipitation, water surging upwards under very high pressure due to relatively high altitude of recharge area, the spring discharge reaches periodically 4–5 $m^3 \cdot s^{-1}$ (Photo. J. Karteczka); B – October 2009, spring discharge very low due to lack of precipitation (Photo. J. Pociask-Karteczka).

Park (Table 6.1). The variability of river discharge is considerable. For instance, the mean annual maximum discharge of the Bystra and Strążyski creeks is 1900 and 850 times higher than mean annual minimum discharge respectively.

There are some wetlands (4.9 km^2) and numerous lakes in the Tatra National Park. Lakes occur mostly in the High Tatra Mountains (Franczak et al. 2015). The majority of lakes has a glacial origin. Cirque lakes and bedrock-moraine dammed lakes are located at the elevation over 1400 m a.s.l. in the Western Tatra Mountains, and over 1600 m a.s.l. in the High Tatra Mountains (Franczak et al. 2015). There are i.a. paternoster lakes – a series of stair-stepped lakes in individual basins aligned down the course of a valley) and inter-sheepback lakes. Small karst lakes occur locally. The lake retention in the whole Tatra Mountains reaches 40 million m^3, and only the Wielki Staw Polski stores 25% total volume of lakes (Łajczak 2006, Table 6.2).

Sustainable exploitation

The history of exploitation of the Tatra Mountains water dates back to the turn of the 19th and 20th centuries, when Zakopane (a reasonably small settlement) transformed into touristic, leisure and spa center. The growing number of inhabitants and visitors entailed the need to expand the infrastructure and the water supply system. The waterworks were designed to supply 20,000 residents and spring water intake was located close to Kuźnice. Works were started in 1905 and the system was implemented in 1906 (Photo. 6.2). This merit should be attributed especially to the Earl Władysław Zamoyski.

At present water resources in the Tatra National Park and its vicinity have been operated by the Water Supply and Sewage Operations Company in Zakopane (SEWiK). The scope of activities of SEWiK includes water treatment and supply, wastewater collection and treatment of sewage water. The share of water gained for the water supply system from streams is ap. 73%, from springs ap. 27%, while from the groundwater aquifers ap. 0.01%. The quality of water is very good, the water does not require advanced treatment techniques (Dzioboń 2012, Kłos 2015). There are strong fluctuations in ground water level and river runoff throughout the year. Zakopane may be considered to be a ”water rich city” from spring to

Table 6.1. River catchments in the Tatra National Park and annual discharge characteristics: average (Q), maximum (Q_{Max}) and minimum (Q_{Min}).

No.	River – gauge station	Area	Q	Q_{Max}	Q_{Min}
		[km^2]	[m^3·s^{-1}]		
1	Czarny Dunajec – Kojsówka[1]	93.7	3.31	88.0	0.35
2	Potok Kościeliski – Kiry[2]	34.5	1.70	15.6	0.36
3	Potok Strążyski – Dolina Strążyska[2]	4.1	0.19	15.3	0.018
4	Bystra – Kuźnice[3]	16.2	1.15	76.0	0.04
5	Potok Olczyski – Jaszczurówka[3]	5.6	0.58	15.2	0.12
6	Poroniec – Poronin[1]	78.8	1.62	32.0	0.32
7	Białka – Łysa Polana[1]	63.1	3.13	43.0	0.52
8	Cicha Woda – Harenda[1]	58.4	2.16	43.5	0.52

[1] 1961–2000 – after Pociask at al. 2010; [2] 1966–2000 – after Kot et al. 2006; [3] 1961–1980 – after Łajczak 1996.

Table 6.2. The largest lakes in the Tatra National Park (Franczak et al. 2015).

No.	Name	Altitude	Area	Depth	Volume
		[m a.s.l.]	[ha]	[m]	[m^3]
1	Morskie Oko	1395	34.39	50.8	9 904,300
2	Wielki Staw Polski	1665	34.35	79.3	12 967,000
3	Czarny Staw pod Rysami	1580	20.64	76.4	7 761,700
4	Czarny Staw Gąsienicowy	1624	17.44	51	3 798,000
5	Czarny Staw Polski	1722	12.69	50.4	2 825,800
6	Przedni Staw Polski	1668	7.71	34.6	1 130,000

Photo. 6.2. A building of Zakopane water supply system in the beginning of the 20th century (Dzioboń 2012).

autumn, but there is a deficiency of water in winter. In summer months and in September and October, when the tourist traffic in Zakopane and in the Tatra National Park is the biggest, water consumption is very high.

Several springs in the Tatra National Park have been used for a variety of human needs, including domestic water supply (i.a. Kórnickie, Gonciska, Jedle springs). Water intakes are located both inside of the Park (near the mountain lodges) and out of the Park – close to its border (Fig. 6.2). A specific water intake has been located in the north-central part of the Park, where groundwater has been gained by adits in ancient iron mine (the Jaworzynka valley).

River water intakes occur in majority of mountain creek catchments (Chochołowski, Kościeliski, Małołącki, Bystra, Olczyski, Białka) and supply the water needs for both domestic purposes and public services in the Zakopane region and mountain lodges (Fig. 6.2). There are water intake for artificial snowing in the Bystra creek on the border of the Park (Photo. 6.3). Water from Chochołowski Creek has been used for a small power plant put into operation in 1958 near the mountain lodge in the Chochołowska Valley. And also water of the Bystra creek is exploited in the electric power plant (2 x 140 kW), which has been operating in the Tatra National Park in Kuźnice since 1915. The power plant was built by Earl Władysław Zamoyski on the foundations of the paper mill operating there in 1884-1895.

Surface fresh water intakes from lakes are located in the Morskie Oko and Przedni Staw Polski (Fig. 6.2). Water has been used in two mountain lodges for household purposes and public services. The mountain lodge by Morskie Oko Lake is visited by almost ⅓ of annual number of tourists visiting the Tatra National Park (ap. 700 thousand). There is also water intake in the lake Wielki Staw Polski for the electricity production. The electric power plant completed in 2010 (80 kW) enabled the construction of a modern biological wastewater treatment plant for the mountain lodge – energy is also used for lighting, heating, and preparation of hot water for various purposes. The ecological effect has been strengthened by

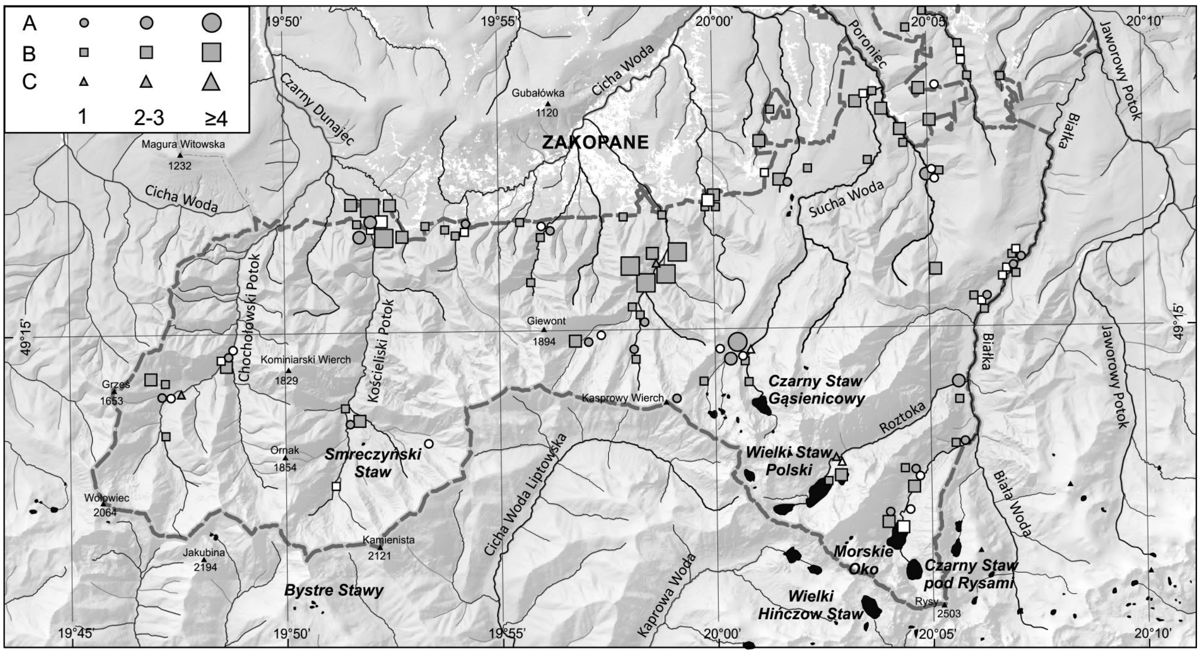

Fig. 6.2. Objects related to water use in the Tatra National Park and its vicinity (A – sewage treatment plants and septic tanks, B – water intakes, C – hydropower plants, 1, 2… – number of structures; empty figure means operating structures and shaded figure means disused structures; Zubek, Pęksa 2015, modified).

Photo. 6.3. Water intake at the Bystra creek. Marek Pęksa representing the Tatra National Park staff (in the middle of the group) explains water resources issue to the participants of the 1st International Tatra Hydrological Workshop in 2012 (Photo. J. Pociask-Karteczka).

thermo-modernization of the building, which reduced energy demand.

In summary, present day water resources exploitation in the Tatra National Park has been tending to be sustainable. There are 44 water users in the Tatra National Park. The SEWiK Company is a main user and it has an access to use 1100 $m^3 \cdot h^{-1}$ of surface water and 370 $m^3 \cdot h^{-1}$ of groundwater (springs) in the Tatra National Park. The surface water exploitation is estimated as 40 mln m^3 per year; about 80% of this water has been used for electricity production, 19.9% for municipal purposes, and 0.1% for artificial snowing. Sewage treatment plants are operating by the mountain lodges. There are also numerous septic tanks located at points by entry gates to the Park and along touristic routes inside of the Park (Zubek 2017).

Study and monitoring of water resources in the Tatra National Park

A knowledge concerns to surface water and groundwater in the Tatra Mountains is very important for a proper management and protection of nature. Water monitoring system serves data for appropriate water resources management. The hydrological monitoring in the Tatra National Park was initially introduced in the 1970. by the research group of Prof. Danuta Małecka, and developed then by Grzegorz Barczyk, who focused on karst hydrology (Barczyk 2006, 2010; Małecka 1985, 1996). The hydrological monitoring carried out by the Tatra National Park started in 2003 and was resumed in 2009 with the financial support of the National Fund for Environmental Protection and Water Management. This moni-toring system consists of 21 points where water quality has been controlling and 42 automatic hydrological stations has been operating to measure the water temperature and water level in creeks (Pęksa 2010). The primary objectives of monitoring are to control:

- surface water quality in river and lake catchments and karstic springs,
- impact of mountain lodges to surface water quality,
- chemical composition of water in caves,
- water balance in stream catchments with karst springs.

There are various scientific projects conducted by researchers representing universities (Pęksa at al. 2011):

- water temperature and ice cover in Morskie Oko (Adam Choiński, Adam Mickiewicz University, Poznań),

– spatiotemporal variability of physical and chemical characteristics of water (Mirosław Żelazny, Jagiellonian University, Kraków),
– evaluation of pollution impact on water ecosystems (Evžen Stuchlik, Charles University, Prague).

There are some research financed by State Forests Found, as follow:
– assesing of the abundance of water in ecosystems (Mirosław Żelazny, Anna Wolanin, Łukasz Pęksa),
– wind-induced deforestation impact on hydrochemical regime and denudation in the forest zone (Mirosław Żelazny).

Protection and nature protection tasks

Institutions, organizations and nature protection networks related to the Tatra National Park and its neighboring waters are: MaB Reserve, NATURA 2000, NATURA 2000 PLC120001 TATRY, RAMSAR, Zakopane county authority, municipalities of Bukowina Tatrzańska, Poronin and Kościelisko, Forest Community of 8 Entitled Villages and the Polish Anglers Association. In 1992, the MaB Committee proclaimed both Polish and Slovak Tatra National Parks as the Tatra Mountain International Biosphere Reserve. Total area of UNESCO Biosphere Reserve in the Tatra Mountains and surroundings covers about 1344.48 km^2, divided into three zones (core, buffer and transitional; Krzan at al. 1996). The area NATURA 2000 PLC120001 TATRY covers ap. 210.45 km^2 (Mróz at al. 2011).

Water resources in Tatra National Park are protected by several law acts issued by European and Polish governments as follow (http://www.apgw.gov.pl):
– Water Framework Directive 2000/60/EC – Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy,
– The Act of 27 April 2001, The Environmental Protection Law,
– The Act of 16 April 2004 on the Protection of Nature.

The Ministry of the Environment of Poland obligates the Tatra National Park administration to follow the following nature protection tasks (Table 6.3):
– an identification and evaluation internal and external threats (existing and potential),
– methods of elimination of threats,
– framework for mitigation of environmental impacts,
– determination of devices of active protection of ecosystems, with kinds, extent and location of respective tasks.

Table 6.3. Threats for water ecosystems, methods, and devices of their elimination or mitigation their effects in the Tatra National Park.

Type of threat	Disclosure	Methods and devices
Internal existing	Overexploitation of streams, lakes and springs	Monitoring the water intake quantity. Assurance of environmental flow in river channels. Diminishing of water intakes in the Park. Monitoring of water level. Prevention of water waste and disturbance of natural water circulation with education and technical technologies.
	Water and soil contamination	Maintenance, construction and modernization of sewage treatment plants and sewage pipelines for buildings in the Park and its neighborhood. Maintenance and modernization of public toilets close to the touristic trails. The analysis and evaluation of specific land use plans according to water and sewage management. Physical and chemical characteristics of surface and ground waters monitoring. Monitoring the water intake quantity. Monitoring the quantity and quality of sewage produced in the Park. Monitoring technical technologies and chemical reagents used in the Park.
External existing	Narrowing down of ecological corridors connecting the Tatra Mountains with neighboring nature protected areas	Prevention of migratory barriers (hydrotechnical constructions).
External potential	Continuation of narrowing down of ecological corridors connecting the Park with neighboring nature and forest protected areas	Initializing and supporting of ecological corridors assignation of specific land use plans. Prevention of migratory barriers (hydrotechnical constructions).
	Excessive growth of tourists	Monitoring of touristic traffic. Permanent and periodic limitations of tourist access to the most visited areas in the Park.

The Tatra National Park has a range of activities and methods to protect ecosystems with respective tasks (Table 6.4). The Park area visited by millions tourist per year requires a constant care and treatment. For instance, there was disposed ap. 576 m^3 of rubbish, and ap. 600 m^3 of waste from 28 cabins in the winter season and 100 cabins in the summer season from the Tatra National Park in 2016 (Zubek 2017).

Education

Important practice to preserve water resources and water ecosystems in the Tatra National Park is ecological education concerning the water. The Educational Department of the Tatra National Park has been introduced several kinds of it. Topics concerning water and water ecosystems are implemented along the educational trails in the Park (Palenica Białczańska–Morskie Oko, Dolina Białego–Sarnia Skała, Amphibia and Reptil Preservation Center in Jaszczurówka). There is also the one-act theater for children ragarding to potential human impact on water ecosystems (Fig. 6.3). Numerous books and booklets popularizing knowledge about water and water ecosystems are published by the Tatra National Park, and they play important role in educational system.

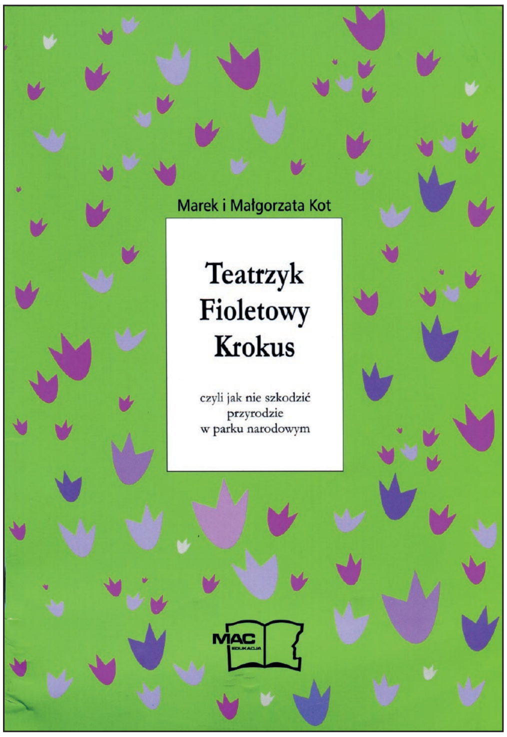

Fig. 6.3. The book cover of the environmental education book "Teatrzyk Fioletowy Krokus" (2003) written for children by Małgorzata and Marek Kot – the Tatra National Park staff.

Educational and information boards related to water were introduced in 2016 in the Tatra National Park. Tourist may take or drink a high quality spring water there (Photo. 6.4). The use of water filling stations will reduce the big amount of empty plastic bottles thrown away by tourists in the National Park. Cleaning streams and lakes actions are organized periodically both for remove rubbish from river channels and for educational purposes. An example of the cleaning of streams may be the event organized in 2017 bythe Tatra National Park with the Geberit Company, when 156 pupils took part in the event. Every year educational staff of the Tatra National Park takes part in the World Snow Day celebration in Zakopane. It provides opportunity to teach the public about snow and consequences of artificial snowing on natural environment. Water resources and water ecosystems are also present in the topic of educational program "Bliżej Tatr" (Closer to the Tatras) dedicated to pupils of primary schools in the region, and also in the contests of knowledge about the Tatra National Park organized by educational staff of the Park for school pupils in the region of Podhale.

Discussion – efficency of water management

Is an effective protection of water resources in the Tatra National Park in the future realistic or not? The existing conflict between exploitation of water and nature protection is growing up. Water is necessary for tourists visiting Zakopane and its vicinity, and for artificial snowing. It will be necessary to change the existing model of water management in the Park due to increas-

Table 6.4. Protection tasks in the Tatra National Park and implementation methods.

Type of task	Method
Monitoring of quantity and quality of surface water and groundwater	20 measurement points in conservation protection area. 15 measurement points in active protection area. 10 control points in landscape protection area.
Cleaning up of rubbish	As needed.
Setting of toilets cabins	32 cabins in conservation and protection area. 43 cabins in active protection area. 26 cabins in landscape protection area.

Photo. 6.4. Drinkwater filling point with educational board in Kuźnice – the Tatra National Park (Photo. M. Kot).

ing water demand. It will be necessary to hammer out the solution with the problem of artificial snowing inside the Park, in particular at the Kasprowy Wierch ski slopes. The analysis of the potential effects of this has shown that permitting artificial snowing will cause a deterioration of natural environment (Kot part of the Kasprowy Wierch represents crystalline rock geology). Artificial snowing would cause a longer snow cover period and shorter vegetation period and moreover, the noise and increasing human presence (skiers) would improperly affect the animal behavior (Fig. 6.4).

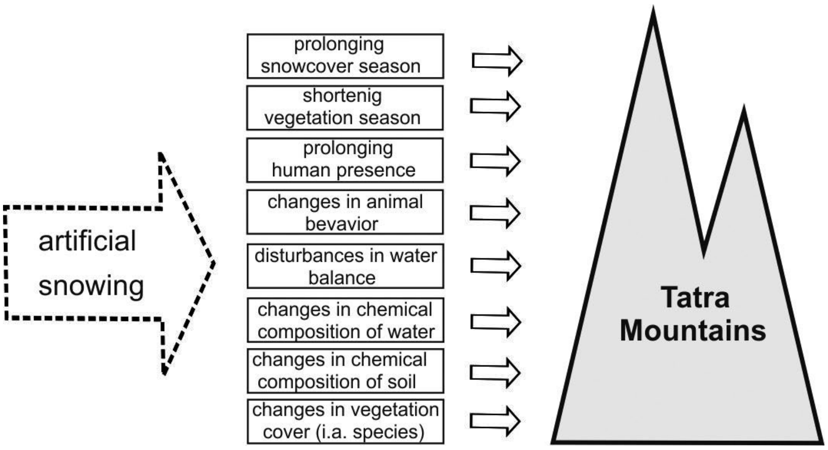

Fig. 6.4. Environmental impact of artificial snowing in the Tatra Mountains – links and effects.

2010). Potential effects of the artificial snowing are: changes in the water balance of the drainage basins below the water intakes and in the snowed drainage basin, and changes in chemical composition of water and soil. Furthermore, the mentioned effects would influence changes in vegetation cover and plant species – especially in case of the usage water from the Bystra creek catchment reach in calcium (the elevated

To conclude, it may be said that the ecological status of water according to the Directive 2000/60/EC, the Park projects referring to the nature protection, the hydrological monitoring network (addressed to controlling the influence of human activity in the high mountain catchments), and ecological education of society, will contribute to sustainable water resources management in the Tatra National Park.

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